ECONOMIC INVESTIGATION OF DISCOUNT FACTORS FOR AGRICULTURAL GREENHOUSE GAS EMISSION OFFSETS

A Dissertation

by

MAN-KEUN KIM

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

DOCTOR OF PHILOSOPHY

May 2004

Major Subject: Agricultural Economics

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ABSTRACT

Economic Investigation of Discount Factors
for Agricultural Greenhouse Gas Emission Offsets. (May 2004)
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This dissertation analyzes the basis for and magnitudes of discount factors based on the characteristics of greenhouse gas emission (GHGE) offsets that are applied to the GHGE reduction projects, concentrating on agricultural projects. Theoretical approaches to discount factors, estimation and incorporation of discount factors procedures are developed. Discount factors would be imposed by credit purchasers due to noncompliance with regulatory program of the credits with GHG program including consideration of shortfall penalties and limited durations. Discount factors are proposed for (i) additionality, (ii) leakage, (iii) permanence, and (iv) uncertainty.

Additionality arise when the region where an AO project is being proposed would have substantial adoption of the AO practice in the absence of GHG programs (business as usual GHGE offset).

Leakage arises when the effect of a program is offset by an induced increase in economic activity and accompanying emissions elsewhere. The leakage effect depends on demand and supply elasticities.

Permanence reflects the saturation and volatility characteristics of carbon sequestration. Carbon is stored in a volatile form and can be released quickly to the atmosphere when an AO practice is discontinued. The permanence discount depends on the project design including practice continuation after the program and the dynamic rate of offset. Also, consideration of multiple offsets is important.

Uncertainty arises due to the stochastic nature of project quantity. The uncertainty discount tends to be smaller the larger the size of the offset contract due to aggregation over space and time.

The magnitude of these discounts is investigated in Southeast Texas rice discontinuation study. The additionality and the leakage discounts are found to play an important role in case of rice lands conversion to other crops but less so for pasture conversions and yet less for forest conversions. The permanence discount is important when converting to other crops and short rotation forestry.

When all discounts are considered, rice lands conversion to forest yields claimable credits amounting to 52.8% ~ 77.5% of the total offset. When converting rice lands to pasture, the claimable credits 45.1% ~ 64.2%, while a conversion of rice lands to other crops yields claimable credits 38.9% ~ 40.4%.

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CHAPTER I

INTRODUCTION

Global Climate Change and Kyoto Protocol

Naturally occurring greenhouse gases (GHGs) include water vapor, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and ozone (O_3) (US EPA, 2001). All are continuously emitted to and removed from the atmosphere by natural processes on Earth. However, human activities, primarily burning of fossil fuels and changes in land cover, have caused an increase in GHG emissions. In turn, atmospheric GHG concentration increases are strongly implicated as contributors to climatic changes that have been observed during the 20th century (McCarthy *et al.*). GHG emissions (GHGE) and concentrations are expected to continue to increase.

Increased atmospheric GHG concentrations produce radiative forcing by changing either the reflection or absorption of solar radiation, or the emission and absorption of terrestrial radiation (Houghton *et al.*). During the 20th century, the Intergovernmental Panel on Climate Change (IPCC) asserts that global average surface temperature rose approximately 0.6°C (1.0 °F) due to these changes (Houghton *et al.*).

Changes in atmospheric GHG composition are likely to alter temperatures, precipitation patterns, sea level, extreme events, and other aspects of climate on which

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the natural environment and human systems depend (McCarthy *et al*.). Regarding agriculture, climate change is expected to vary the growing environment for agricultural production, and in turn affect yields, regional production characteristics, resource usage, and market conditions (Adams *et al*., 1990; Mendelsohn, Nordhaus, and Shaw; Adams, Hurd, and Reilly).

The issue of climate change has become a widely discussed policy topic because of its potential consequences and its inherent complexity. The IPCC asserts that climate change effects may be irreversible and that resultant damages are uncertain. Numerous researchers believe that negative impacts of climate change will likely outweigh benefits (Bruce, Lee, and Haites; Zelek and Shively), although economic and ecological consequences of climate change are a subject of debate (Reddy and Price).

Recognizing possible adverse impacts caused by global climate change, 165 countries negotiated and signed the United Nations Framework Convention on Climate Change (UNFCCC), which sets a goal of long-term stabilization of GHG concentrations in atmosphere at a level that would prevent dangerous human interference with the climate in 1992 (United Nations, 1992)

In 1997, the conference of the parties to the UNFCCC yielded the Kyoto Protocol (KP), which sets emission limits on CO_2 and other GHGs commencing with the period 2008 – 2012 (UNFCCC). The KP contains emission targets and timetables for 39 industrialized countries, mainly developed nations in North America, Europe, Asia and Australia. The KP requires participating countries to reduce GHGE by 5 to 8 percent relative to the 1990 emission levels during the first commitment period. The U.S. KP obligation was to reduce emission by seven percent.

However, in 2001, the U.S. announced that it would not participate in the implementation of the KP (White House, 2001). The Bush Administration objected to the KP on three reasons: (i) lack of a long-term goal based on science, (ii) exclusion of developing nations such as China and India, whose GHGE are projected to grow rapidly, and (iii) economic costs of mitigation actions. Later, President Bush announced an emission reduction program that involves an 18 percent reduction in GHGE intensity (emissions per dollar GDP) by 2012 (White House, 2002). This plan is estimated to be less restrictive than the KP plan.

Agricultural GHGE Offset

One of the mitigation alternatives includes the development of Agricultural GHGE Offset (AO) activities in the form of emission reductions and/or carbon sequestration. Several studies examine the possibility that agricultural producers can reduce emissions and sequester carbon by adopting management or land use changes (Rausmussen and Parton; Lal *et al.*; McConkey and Lindwall; McCarl and Schneider, 2000, 2001). Considerable attention is focused on the possibility of encouraging the AO practices because it may be a relatively inexpensive way to reduce net GHGE (National Academy of Sciences; Bruce, Lee and Haites; McCarl and Schneider, 2000, 2001).

There are at least four ways agriculture may participate in or be influenced by GHGE mitigation efforts; (i) Agriculture is a source of GHGE and may need to reduce net emissions, (ii) Agriculture may enhance its absorption of GHG from the atmosphere by creating or expanding sinks, (iii) Agriculture may provide products which substitute for GHGE intensive products by for example producing bio-fuels and (iv) Agriculture may find itself operating in a world where commodity and input prices have been altered by GHGE related policies (McCarl and Schneider, 2000). AO projects mainly relate to ways (i) through (iii) above.

When pursuing a GHGE mitigation program, it will be important for society to detect low cost options. AO practices may be attractive because they can be a relatively inexpensive way to reduce net GHGE as well as a ways to increase economic opportunities for agricultural producers (Dixon *et al*.; Sampson and Sedjo; Marland and Schlamadinger). Also AO practices can be appealing since they can contribute to other agricultural and environmental goals (co-benefits) by increasing biodiversity or decreasing soil erosion (McCarl, Murray and Antle).

There are two major types of practices that can be employed to offset GHGE via agriculture: changes in land management and changes in land use. The commonly discussed management changes involve changes in crop mix, tillage systems, nutrients applied and residue management. Changes in land use involve conversion of croplands to other crop mix, pastureland, or forest establishment (Post and Kwon; McConkey and Lindwall; McCarl, Murray and Antle).

Many U.S. GHGE offset policy proposals in the AO arena emphasize the allocation of agricultural lands to forest uses, so-called, afforestation option (Parks and Hardie). For land-rich countries like the U.S., Canada, and Russia, AO projects can potentially account for significant emission reductions (Feng, Zhao and Kling). According to U.S. Department of State, the U.S. could meet half of its emission reduction commitment under the Kyoto protocol using agricultural soil sinks, combination with forest sinks.

Economic Considerations

There are numerous economic considerations involved with the potential proliferation of AO strategies. The most important consideration is trading of project GHGE credits in the market. Credit buyers such as large GHG emitters will purchase the credits if the credits cost less than the cost within their operation to reduce an additional unit of GHG. And credit sellers, who may be agricultural producers adopting an AO project, will sell the credits based if they can be fully compensated for any extra costs incurred to reduce or sequester an additional unit of GHG through the AO project.

From the credit buyer's point of a view, buying a GHGE credit produced by an AO project is no different from buying offset generated by other GHGE mitigation options such as direct GHGE reductions. They will prefer the credits from an AO project when these credits are cheaper than credits from other GHG offset sources. Conventionally, direct GHGE reductions are related with reduced use of fossil fuels from improving energy efficiencies, increasing conservation, or shifting to non-fossil energy sources, etc. It is argued that if a ton of fossil fuel is not used, its emissions are avoided forever. However, as pointed out by Noble *et al*., and Herzog, Caldeira and Reilly, the idea that a ton of fossil emissions avoided today is avoided forever is not necessarily an accurate characterization of the problem because that unburned fossil fuel may still be mined and burned later.

In this sense, it is important to recognize that credit buyers will compare AO projects with other mitigation options in an effort to assemble a minimum cost portfolio. These comparisons should be made based on offset characteristics of the quantity of GHGE offset created by each alternative and the ways such offsets can be claimed under society wide offset accounting rule and whether these offsets will totally be creditable in a GHG program.

For this comparison, there is a need to determine how AO project offsets will be considered as a credit. In order to measure or monitor the GHGE credits created by the AO project, we should consider GHGE offset characteristics discounts as will be discussed below. Relevant characteristics that may be lead to discounts are related to as additionality, leakage, permanence, and uncertainty.

GHGE Offset Discounts

When an AO project is under consideration, there are some possible discounts that may arise based on the characteristics of GHGE offset in terms of additionality, leakage, permanence, and uncertainty. These factors may reduce the effective GHGE offset.

Additionality

Most GHG projects involve a discrete switch in technologies or choice of actions: fossil fuel to non-fossil fuel, forest protection versus forest conversion (Chomitz, 2002). For project-based GHGE credits, it is important to determine whether this switch would have occurred under business-as-usual. If so, the project is not additional (Chomitz, 2002). According to the KP, GHGE reductions from a Clean Development Mechanism (CDM) project should be additional to any that would occur in the absence of such activities (UNFCCC, Article 12).

In the AO project context, additionality is a concern when the region where a project is being proposed has had substantial historical adoption of the AO practice before any GHG programs were implemented and is expected to have additional adoption in the future. In such a case a discount for the region may need to be developed to reflect business-as-usual AO practices adoption.

Additionality can be summarized in the form of the following question:

> *Before the AO project goes into effect to reduce net GHGE, are there any of the projects which are already used and are projected to be used in the future without AO related incentives?*

Leakage

When an AO project succeeds in a place, it can potentially reduce supply of agricultural products, and stimulate GHGE elsewhere. Namely, market forces may encourage additional economic activities and associated GHGE in another regions, thereby offsetting the reduction in GHGE. To the extent that this happens, the AO project leaks with its GHG offset being reduced by GHGE increases elsewhere.

Leakage occurs when actions to reduce net GHGE cause alterations in market conditions (e.g. price effects) that induce emission increase elsewhere (see Murray, McCarl, and Lee for a review of the concept and literature). It is noteworthy that leakage effects may be substantial because agricultural markets are highly competitive and demand and supply are relatively inelastic. Leakage can be summarized as following question:

> *If an AO project succeeds, will the GHGE reduction would be offset by marke tinduced alterations in practices elsewhere that offset the project induced reduction in net GHGE?*

Permanence

Offsets of GHGE using agricultural soil carbon sequestration are not necessarily permanent. Once an AO project is put into place, annual carbon offsets realized may diminish in the long term as the soil and vegetation reach a new equilibrium under the land use practice. Furthermore, when the AO practice is discontinued, the carbon is often released quickly (volatile) to the atmosphere.

In this case, we need discounts for comparing the emissions offset versus the benefit gained if the carbon storage were permanent. Permanence can be summarized in the following question:

> *If the AO project increases absorption of the carbon into the biosphere, will the carbon stay there? What happens when AO incentives are discontinued or the project life expires?*

Uncertainty

There are a variety of uncertainties related to an AO project. The sources of uncertainty include variability in the quantity of GHGE offset; sampling error (aggregation error) at regional scales; carbon pool measurement errors; and limitations in understanding processes controlling future GHGE implications (Birdsey and Heath; Heath and Smith). The term uncertainty describes phenomena such as statistical variability, lack of knowledge, or surprise. Uncertainties in quantifying GHGE offset may be caused by lack of knowledge. Also, extreme events such as a forest fire may be categorized as surprise.

The GHGE offsets generated by an AO project may need to be discounted to reflect uncertainty. The simplest way is to represent uncertainty is in the form of a confidence interval based on probability density function (PDF). Uncertainty can be summarized as following question:

> *Is the quantity of offset uncertain in an AO project? Would buyers or regulators be interested in a more certain measure of offset volume than the mean?*

Who Imposes GHGE Offset Discounts?

As argued above, credit buyers only choose AO projects when the credits evaluated by such projects are cheaper than other GHG offset opportunities. In order to compare two possibilities, it is important to determine how much GHGE offset the AO project really creates that can be considered as a credit, and thus, an estimate of GHGE offset that may be disallowed. Also, a government or a regulatory agency needs to figure out how much GHGE credits an AO project creates.

Objectives and Organization of the Dissertation

The objective of this study is to contribute to develop procedures to apply, and estimate applicable discounts in the form of additionality, leakage, permanence, and uncertainty. To do this, the work will include (i) development of a conceptual framework for the identification of GHGE offset discounts, (ii) development of usable formulas for discount estimation, and (iii) investigations of the empirical magnitude of the discounts in a case study context.

This dissertation is organized as follows. Chapter II discusses agricultural GHGE offset including carbon sequestration and introduces the conceptual framework for the GHGE offset discounts. In turn, individual investigations of the discounts and estimation procedures regarding additionality, leakage, permanence, and uncertainty are presented in Chapters III through VI. Investigations of the empirical magnitude of the GHGE discounts for a Southeast Texas appear in Chapter VII. Chapter VIII contains concluding remarks.

CHAPTER II

GHGE OFFSET DISCOUNTS AND QUANTITY OF GHGE OFFSET

Background

An AO project are not done entirely in isolation and as a consequence, the quantity of GHGE offset may be subject to discounts due to concerns of additionality, leakage, permanence and uncertainty. Applying discounts reduces the quantity of GHGE offset to the truly salable quantity of GHGE offset, which becomes GHGE credit. Note that the extent of discount GHGE offset depends upon the GHGE regulatory standard.

As argued in Chapter I, it is important for credit buyers to compare AO projects with other mitigation options as other investment portfolio. These comparisons should be made based on economic variables such as the expected carbon price, interest rate and the quantity of GHGE offset created by each alternative. The AO program is considered as one of a possible investment because the AO program is not different from direct GHGE reductions from a credit buyer's point of a view (Herzog, Caldeira, and Reilly). For doing this, there is a need to determine how much creditable GHGE offsets creates. In order to measure the GHGE credits created by the AO project, we need to consider GHGE offset discounts such as additionality, leakage, permanence, and uncertainty.

GHGE Offset Discount

As a common discount procedure, the GHGE credit (Q_C) is calculated by $Q_C = Q \times (1 - \delta)$ where, Q is the quantity of GHGE offset and δ is the GHGE discount ($0 \leq \delta \leq 1$), the amount of not creditable or the credits only for a limited time relative to regulatory program length. Thus, the GHGE discount is simply expressed as follows:

$$(1) \qquad \delta(\%) = \left(\frac{Q - Q_C}{Q} \right) \times 100 = \left(1 - \frac{Q_C}{Q} \right) \times 100 \, .$$

Carbon Prices and GHGE Discounts

Essentially AO projects contribute credits to firms' long-term offset requirements so that we need to introduce explicit carbon price path and interest rate when we consider GHGE discounts. Now we define the net present value (*NPV*) of the benefits of gains from the AO project as follows:

$$(2) \qquad NPV^0 = \sum_{t=0}^{T} P(t)Q(t)(1+r)^{-t}$$

where *P* is the carbon price, *r* is the interest rate, and *t* is the time (year). The superscript, 0, indicates a perfect prospect that is free of concerns on additionality, leakage, permanence or uncertainty over time. When we are concerned with additionality, leakage, permanence or uncertainty, then *NPV* of the benefits from the AO project is:

$$(3) \qquad NPV^1 = \sum_{t=0}^{T} P(t)Q(t)(1-\delta(t))(1+r)^{-t} \, ,$$

or, which under constant discount (δ) becomes:

$$(4) \qquad NPV^1 = \sum_{t=0}^{T} P(t)Q(t)(1-\delta)(1+r)^{-t} = (1-\delta)NPV^0 .$$

From equations (2) and (4), the GHGE discounts can be rewritten as follows:

$$(5) \qquad \delta(\%) = \left(\frac{NPV^0 - NPV^1}{NPV^0} \right) \times 100 = \left(1 - \frac{NPV^1}{NPV^0} \right) \times 100 .$$

Equation (5) can be reduced to equation (1) because the $P(t)$ and $(1 + r)^{-t}$ terms cancel out when the time horizon and $Q(t)$ for NPV^0 and NPV^1 are the same. If the time horizon or emissions are not constant over time (this happens when we deal with permanence issue), then equation (1) and (5) are different and we should use equation (5) to estimate the GHGE discount.

Estimation of Agricultural GHGE Offset and Credit

Once we find NPV^0 and NPV^1 in equation (5), we can compute the GHGE discount. The subsequent section discusses what is the quantity of GHGE offset.

Agricultural GHGE Offset

The quantity of agricultural GHGE offset, Q, consists of three parts in the case of the AO project, (i) carbon sequestration, (ii) saved emissions from production, and (iii) reduction in fossil fuel usage for machinery when tillage is reduced.

Carbon sequestration

When land is transformed from natural forest or grassland to agriculture, a large amount of the native soil organic matter (SOM) is lost as carbon dioxide emitted to the atmosphere.

On the other hand if land management practices are changed to retain more SOM then carbon accumulation may occur which carbon dioxide is effectively removed from the atmosphere and put into the soil. This process is called carbon sequestration (McConkey and Lindwall). Figure 1 illustrates soil carbon changes over time on agriculture lands.

There are two major types of activities that enhance sequestration: (i) changes in land management, and (ii) changes in land use. Changes in land management involve tillage choice, nutrient and residue management such as adopting conservation tillage or no-till, adding organic manure, and/or altering fertilization (Lal *et al.*; McCarl, Murray and Antle). Changes in land use involve (i) conversion of croplands to forest lands, grasslands, pasture, rangelands or wetlands, (ii) conversion of pasturelands to forests lands, and (iii) restoration of degraded lands to reestablish their organic content (McCarl, Murray and Antle).

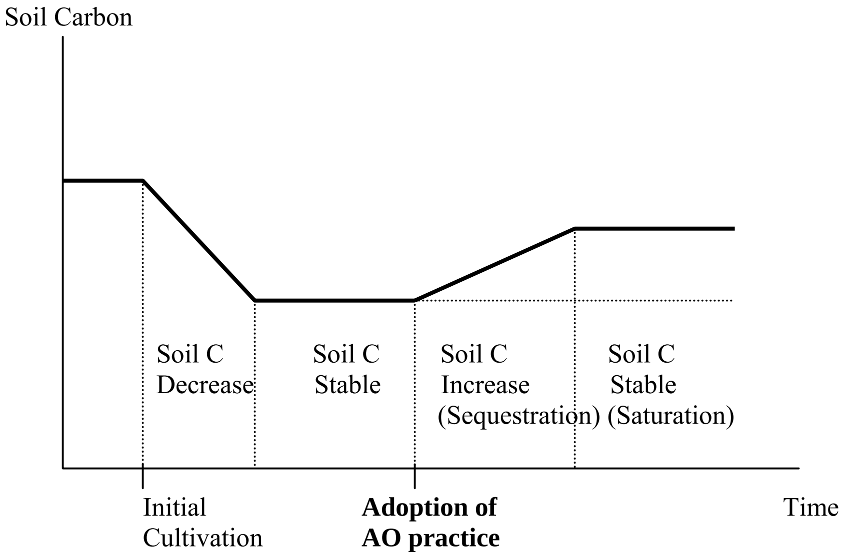

Figure 1. Soil carbon changes and adoption of AO practice
Modified from McConkey and Lindwall

Direct Reduction

Agriculture (including rangelands and forestry) can reduce GHGE directly because agriculture emits GHGs. In particular, agriculture releases substantial amounts of CH_4, N_2O and CO_2. Agriculturally based GHG emissions in developing countries largely arise from deforestation and land degradation. Agriculturally based GHG emissions in developed countries are largely caused by fossil fuel usage, reductions in soil carbon via intensive tillage; nitrous oxide emissions through fertilizer applications, livestock feeding, and residue management; and methane emissions from livestock raising and rice cultivation. Agriculture's global share of anthropogenic emissions has been estimated to be about 50% of total CH_4, 70% of N_2O, and 20% of CO_2.

Agricultural GHGE Credits

As elaborated in subsequent chapters, we consider (i) additionality, (ii) leakage, (iii) permanence, and (iv) uncertainty. The GHGE credit can be calculated as $Q_C = Q(1-ADD)(1-LEAK)(1-PERM)(1-UNCER)$, where *ADD* indicates the additionality discount, *LEAK* the leakage discount, *PERM* the permanence discount and *UNCER* the uncertainty discounts.

Concluding Remarks

In this chapter, we define the GHGE offset discount and the agricultural GHGE offset. The GHGE offset discount arises due to concerns of additionality, leakage, permanence and uncertainty. Applying discounts adjust the quantity of GHGE offset generated by an AO program so it equals the effective amount of salable GHGE offsets which is the

GHGE credit. The GHGE discount is defined as one minus the ratio of the net benefit gained from GHGE credit created by the AO project compared the net benefit gained from GHGE offset.

The agricultural GHGE offset is defined as net reductions in agricultural GHGE coupled with net increases in carbon sequestration. Changes in land management and changes in land use can lead to reductions in GHGE and enhancement of GHG sinks.

CHAPTER III

ESTIMATE OF ADDITIONALITY DISCOUNT

Background

Most GHG projects involve a discrete switch in technologies, management or land use, for example, fossil fuel to non-fossil fuel, forest protection versus forest conversion (Chomitz, 2002). For project-based GHGE offsets, it is important to determine whether this switch would have occurred in the absence of GHG projects under business-as-usual. If so, the project is not additional (Chomitz, 2002).

Additionality has been a prominent concern in the international GHGE control dialogue. For example, in the Kyoto Protocol (KP), provisions state that GHGE reductions under the Clean Development Mechanism (CDM) are required to be additional to any that would occur in the absence of such activities (UNFCCC, Article 12).

In the context of an AO project, additionality concerns arise when the region where the project is to be implemented has had substantial adoption of the AO practice before any GHG programs are implemented and that this adoption is projected to continue in the absence of the project. In such a case, the offsets created by the project are not entirely additional and a discount may be needed to reflect business-as-usual AO practice adoption and accompanying net emission reductions.

The basic question is what portion of the GHGE offset benefits would have occurred under business-as-usual, commonly called baseline and thus how much is additionally stimulated by the AO project. If a significant amount of the AO practice would have been adopted naturally, then a discount is in order to reflect non-additional reduction tat cannot be claimed under the regulatory structure.

The following sections conceptualize the problem, develop an analytical approach for additionality and explain the asymmetric information problem between the credit buyers and producers.

Analytical Approach for Additionality

The Basic Problem

As argued in previous chapters, the GHGE credit buyers and the government agency or regulatory agency need to measure GHGE credits or how much GHGE credits are really created. Unfortunately, they are unable to observe the GHGE offset from the adoption of the AO practice at reasonable cost because the GHGE offset is produced widely across the landscape. The credit buyers or the governmental agency can only form expectations conditioned on observations of the land management (e.g., no-till), land use change (e.g., afforestation), other relevant data such as weather, and periodic measurement based on samples. Assume that general form of the agency's GHGE offset is

$$(6) \qquad Q = g(k, w, \varepsilon),$$

where Q is the true GHGE offset from the land use alternatives k (the AO practice) which are unobservable; w is a random variable such as weather and ε is a random variable representing the agency's imperfect knowledge of the Q. Thus, there are two sources of uncertainty about GHGE offset. One is imperfect information about the GHGE offset process itself, denoted by ε and the other is *ex ante* uncertainty about weather condition, denoted by *w*. The credit buyers and agency's joint density for ε and *w* is given by $f(w,\varepsilon)$, then the expected GHGE offset created by the land use *k* is

$$(7) \qquad \overline{Q}(k) = \int\int g(k,w,\varepsilon)\, f(w,\varepsilon) dw d\varepsilon \,.$$

Assume that *MC* denotes the marginal cost schedule for agricultural producers who adopt the AO project to create one unit of GHGE offset in specific area. The marginal cost, *MC*, is the payment required for a producer to adopt and keep the AO practice. Note that *MC* is the function of land use *k* and specialized knowledge of the operation of the farm or producer, θ. The parameter θ is an index of producer profitability (the producer "type") known to the producer but not to the agency. The parameter θ might be interpreted as an index of a producer's managerial ability or an index of soil quality or a composite index of both (Smith and Tomasi).

Additionality with Perfect Information

As argued above, there are uncertainties in *Q* and there exist asymmetric information between the producer and the credit buyers and agency due to the parameter θ. With perfect information, θ is known to the credit buyers and the agency so that they can estimate $MC(k,\theta)$ for the producer who adopts the AO project. The producer who participates in the AO project would receive $MC(k,\theta)\cdot Q$, where *Q* is perfectly observable.

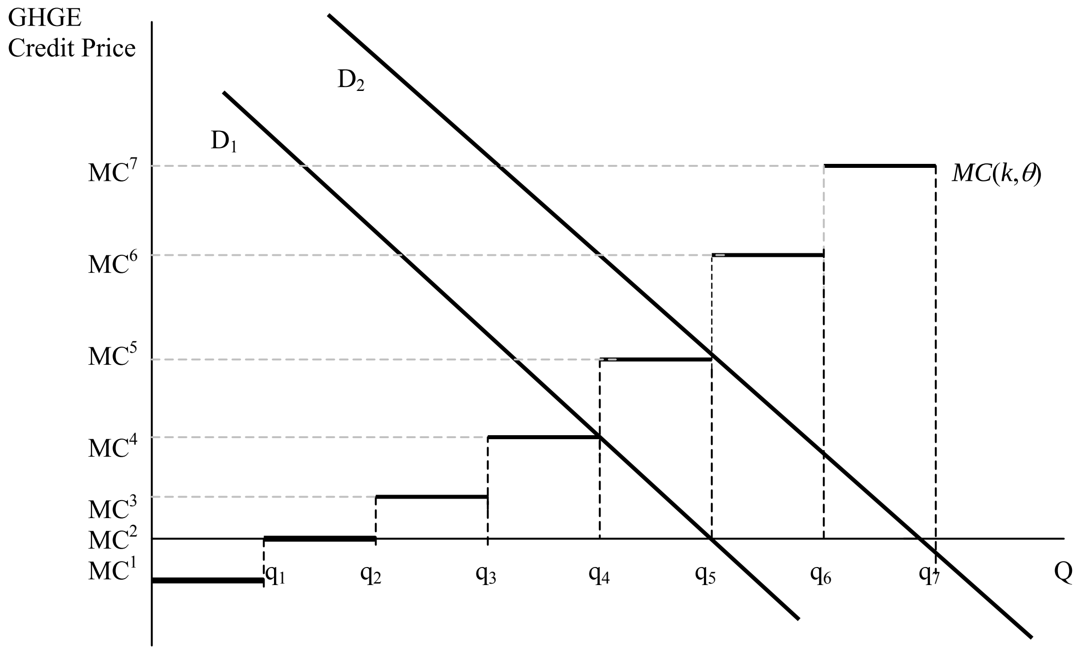

Figure 2. GHGE offset and additionality

It is noteworthy that the producer would convert land to the AO practice under business-as-usual when $MC(k,\theta)$ is less than or equal to zero, because an incentive for producer exists without any GHG program. In such a case, *Q* by adoption of the AO project is not additional. This is illustrated in Figure 2.

Assume that the GHGE offset supply is a step function, which is equivalent to each producer's marginal cost to offset GHGE, that is $MC(k,\theta)$. Suppose that there are 7 types of producers and marginal cost increase with higher values of θ. Also we assume that the GHGE credit demand is a downward sloping linear function, denoted by *D*. When the GHGE offset price offered is $MC(k,7)$ then, all producers will adopt the AO practice and they offset GHGE by q_7, which may be the maximum *Q* in this area.

If the GHGE offset price in the market is $MC(k,4)$, then 4 of producers would change their land use to the AO practice and offset GHGE by q_4. Notice that producer types 1, and 2 have a negative or zero marginal cost so producers 1 and 2 would adopt the AO project voluntarily without any GHG program. Thus GHGE offset q_2 is not additional.

When we compute the salable GHGE offset, that is the GHGE credit, we need to consider this portion in terms of additionality discount. As we can see, salable GHGE credit (Q_C) is ($q_4 - q_2$). If the GHGE credit price increase to $MC(k,5)$ due to larger GHGE credit demand, then producers create q_5 GHGE offset and in turn, $Q_C = (q_5 - q_2)$. From equation (1) in Chapter II, additionality discount (*ADD*) can be found as follows:

$$(8) \qquad ADD = 1 - \frac{Q_C}{Q} = 1 - \frac{(\text{Total Offset} - \text{Baseline Offset})}{\text{Total Offset}} = \frac{\text{Baseline Offset}}{\text{Total Offset}}$$

Based on equation (8), *ADD* is q_2/q_4 when the GHGE offset price is offered by $MC(k,4)$ and *ADD* is q_2/q_5 when the GHGE credit price is $MC(k,5)$. It is noteworthy that *ADD* would be affected by the GHGE offset prices in the market. When the GHGE price is low, *ADD* would be large and when the GHGE price is high, then *ADD* would be small.

Additionality with Imperfect Information

As pointed above, the parameter θ is known to producers but not to the credit buyers and the government agency. From their perspective, θ is a random variable with density function, $h(\theta)$. Therefore, there exists asymmetric information between the agricultural producer and the credit buyers and the agency. Asymmetric access to information is a problem for calculating GHGE credits. Because participation in the AO project is voluntary, certain baseline allocation methods have the risk of selection bias (adverse selection problem) (Fischer).

Producers may be expected to acquire specialized information about their farm operations and they are notoriously reluctant to reveal their profitability to public agencies (Shortle and Dunn). In such a case, the credit buyers and the agency do not observe producer's type and $MC(k,\theta)$ because they cannot discern low-cost producers (for instance, type 1 and 2 producers in the above example) so that the GHGE offset supply curve in Figure 2 cannot be found. In other words, estimate of the additionality discount is impossible.

The existence of such a differential information structure is often assumed in the literature on choices among policy instruments (Weitzman; Adar and Griffin; Roberts and Spence; Dasgupta, Hammond, and Maskin; Shortle and Dunn; Smith and Tomasi; Millock, Sunding and Zilberman).

Economic theory offers ideas for designing contracts to induce project proponents to reduce such distortion, or even to fully reveal what type producers are (Fischer). This involves offering the producers a menu of different combinations of quantities (e.g., production, management, or GHGE offset) and corresponding prices (Chomitz, 1998).

However, Fischer insists that this approach is either impractical or inapplicable because this revelation mechanism assumes that actual GHGE offsets can be established, albeit with a cost to monitoring. In other words, GHGE baseline offsets in the absence of the project cannot be observed although actual GHGE offset can be observed (Bohm).

The most straightforward approach to baseline determination under imperfect information is the direct questioning: asking the producer what would be done in the absence of the GHGE offset project (Chomitz, 1998). However, potential drawbacks of this approach include respondents' inability to deal with hypothetical questions, their incentive to answer strategically, and their reluctant to admit to free riding (Waldman and Ozog).

Another conceivable approach to overcome the asymmetric information problem for computing the baseline is the control group methods: observing the behavior of a comparison group not offered incentives to sell GHGE offsets (Chomitz, 1998). But this approach has drawbacks which include the difficulty in finding a valid control group.

The other approach to baseline determination is the economic modeling such as Agricultural Sector Model (ASM). This means constructing a model describing how producers would behave in the absence of offset incentives and predicting whether the producer would adopt the GHGE project in the absence of offset incentives (Chomitz, 1998). But it is difficult to calibrate the model because some crucial parameters to be specified for model are hard to observe, subject to misrepresentation, subject to strategic manipulation, and subject to change (Chomitz, 1998).

In this paper, we propose a different approach to determine baseline offsets, so called the *project-based approach*. In this approach, we assume all producers in specific area are provided the GHGE offset project monetary incentive, $MC(k,\theta)$. But, as we discussed above, $MC(k,\theta)$ cannot be estimated due to asymmetric information. In determining $MC(k,\theta)$ to be paid, the credit buyers or the government agency considers the amount necessary to encourage producers of eligible land to participate in the GHGE offset program. For doing this, the density function $h(\theta)$ would be conjectured based on producers' historical cropping records, site-based soil productivity, and prevailing local rental rates, etc. Based on the density function $h(\theta)$, $MC^*(k,\theta)$ can be found as follows:

$$(9) \qquad MC^*(k) = \int^{\theta=\theta^*} MC(k,\theta)h(\theta)\mathrm{d}\theta,$$

where $MC^*(k)$ is the maximum marginal cost over producers to offset a certain amount of GHGE. Producers may offer land at this price or offer a lower price to enhance the GHGE offset and their offer will be accepted. For example, when $\theta = 5$, projected GHGE offset is q_5 under this price because type 6 and 7 producers will not participate in this program in Figure 3.

Assume that the credit buyer and the agency can compute the adoption rate for the AO practice based on data such as *historical land transition*. That is, the historical land transition is interpreted as producers' behavior in the absence of the GHGE offset incentives. In this case, *ADD* would be q_2/q_5 when we assume that baseline offset is equivalent to q_2 in Figure 3.

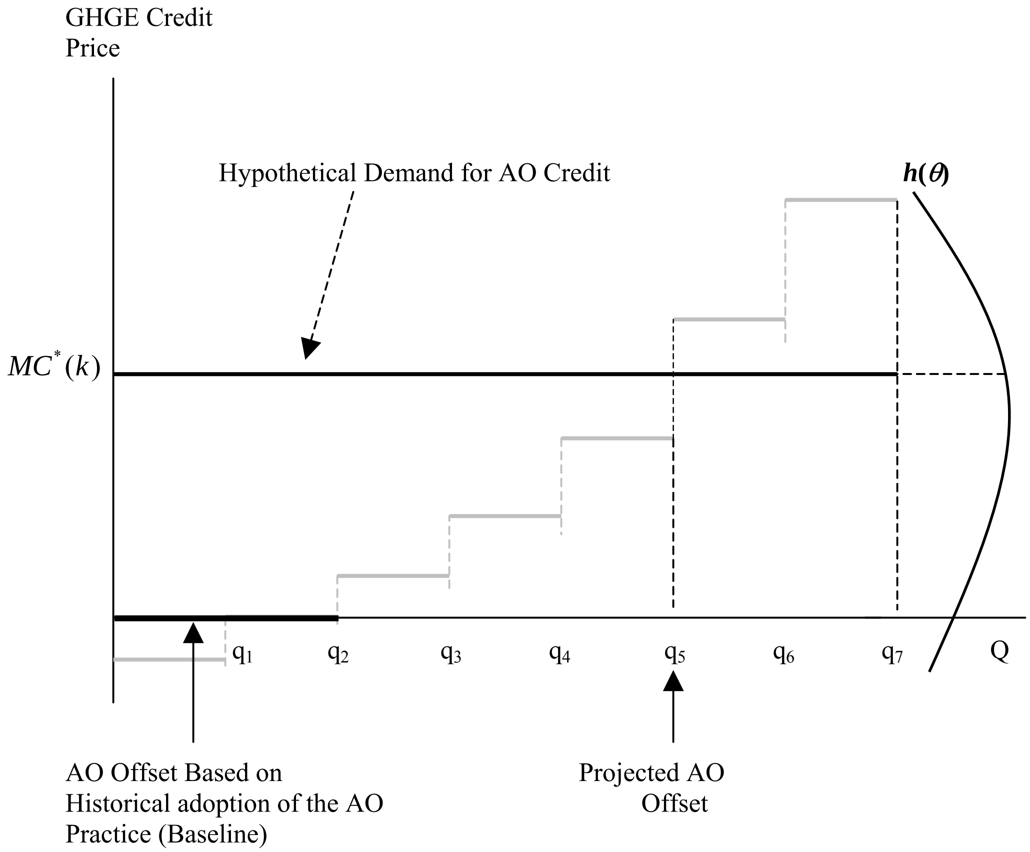

Figure 3. Project-based approach and additionality

Under the project-based approach baseline determination is easy because we need historical data and estimates of expected GHGE offset created by the land use *k* which is provided in equation (7). However, error in the estimate of *ADD* is unavoidable, which is used as the difference between the true *ADD* and the estimated *ADD*, because baseline estimation requires quantification of what does not occur. In other words, precise baseline estimation is impossible so that the estimate of *ADD* should be biased. However, we cannot decide whether it is overestimated or underestimated.

Derivation of Additionality Using Project-Based Approach

As discussed above, actual *ADD* cannot be obtained easily due to asymmetric information. In this section, we formalize the *project-based approach*. We assume that all land managers either voluntarily or through coercion adopt the AO project when the AO project is implemented in the specific region under average GHGE price level. Also, we assume that GHGE credit demand is sufficient to buy all of GHGE offsets created in this area under this price. Finally, we assume that the baseline GHGE offset can be computed based on extrapolation of historical adoption trends for the AO practice.

If the rate of change in land use or the rate of conversion is known, the baseline AO offsets from a set of *k* alternative land use changes or management changes can be calculated as follows. Note that we assume that net AO offset rate (*SR*) is known [1].

$$(10) \qquad B(t) = \sum_{k}^{K} A \cdot CR_k(t) \cdot SR_k(t)$$

where, $B(t)$ is the total amount of baseline GHGE reductions in time t, A is the total project area, $CR_k(t)$ is the baseline proportional rate of adoption of AO alternative k in

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[1] Note that *SR* indicates the per-acre quantity of GHGE offset and *Q* indicates the quantity of GHGE offset. In other words, $A \cdot SR = Q$.

time *t*, and $SR_k(t)$ is net AO offset rate for alternative *k* in time *t*. The net present value of the baseline quantification over time (NPV^B) will be:

$$\text{(11)} \qquad NPV^B = \sum_{t=0}^{T} P(t)B(t)(1+r)^{-t}$$

Now consider an AO project that is implemented in year 0. The net present value of the projected GHGE offset over time (NPV^P) is:

$$\text{(12)} \qquad NPV^P = \sum_{t=0}^{T} P(t)A \cdot SR_{AO}(t)(1+r)^{-t}$$

where, $SR_{AO}(t)$ is net AO offset rate for an AO practice in time *t*. From equations (11) and (12), an additionality discount (*ADD*) can be found as follows after *P*(*t*) and $(1+r)^{-t}$ terms are cancelled out:

$$\text{(13)} \qquad ADD(\%) = \frac{NPV^B}{NPV^P} \times 100 = \frac{\sum_{t=0}^{T} B(t)}{\sum_{t=0}^{T} A \cdot SR_{AOt}(t)} \times 100$$

To demonstrate this, an example is used. First, assume the project activity is afforestation, second, assume the project area (*A*) is 10,000 acres, third, assume the net AO offset rate ($SR_{AO}(t)$) is 1 ton/ac/year of carbon equivalent and this rate remains constant over time. Fourth, assume the program continues for 100 years (*T*). Fifth, assume that baseline rate of afforestation ($CR_k(t)$) is 0.5% per year and that there is only one alternative ($k = 1$) for conversion of project area to forestry. Thus, 0.5% of cropland converts to the forest a year under business-as-usual. In other words, afforestation occurs at the rate of 0.5% in the absence of the AO project.

From the above assumptions, the project GHGE offset is 10,000 tons/year for 100 years and total projected GHGE offset would be 1 million tons. The amount of baseline *cumulative* GHGE offset can be computed as (See Table 1 single offset column):

Year 1: 10,000 acres × 1 ton/ac × 0.5% = 50 tons
Year 2: Year 1 + (10,000 acres × 1 ton/ac × 0.5%) = 100 tons
Year 3: Year 2 + (10,000 acres × 1 ton/ac × 0.5%) = 150 tons
Year 50: 2,500 tons
Year 100: 5,000 tons

The amount of *cumulative* baseline offset would be 252,500 tons. From equation (13), *ADD* is 25%. It implies that 25% of the projected GHGE offsets would have happened *naturally* and thus, GHGE credit should be adjusted downward to only leave the additional portion.

Consider another example that involves multiple land-uses. Assume that $k = 2$ and the under baseline conditions the AO project area would be partially converted to forestlands and pasturelands at rates of 0.25% per year, respectively. Total conversion rate is 0.5% as in above example. If the net AO offset rate is the same in both forests and pasturelands, *ADD* will be the same. But the more interesting case involves differing net AO offset rates. Let's assume that the net AO offset rate of pasturelands is 0.5 tons/ac/yr, which is half of the afforestation rate.

Table 1. Baseline and Project Carbon Sequestration with Single Offset

Year	Single Offset	Multi-Offset		Project
	Baseline	Baseline		
	Forest (ton)	Forest (ton)	Pasture (ton)	
1	50	25	12.5	10,000
2	100	50	25.0	10,000
3	150	75	37.5	10,000
4	200	100	50.0	10,000
5	250	125	62.5	10,000
10	500	250	125.0	10,000
15	750	375	187.5	10,000
25	1,250	625	312.5	10,000
50	2,500	1,250	625.0	10,000
100	5,000	2,500	1,250.0	10,000
Sum	252,500	126,250	63,125	1,000,000

The baseline GHGE offset is 189,375 tons (= 126,250 tons + 63,125 tons) that is a sum of GHGE offset from afforestation and pastureland (See Table 1 multi-offset column). From equation (13), *ADD* is computed as 19%. It implies that 19% of the projected offsets would have happened *naturally* and thus, the GHGE offset should be adjusted downward by 19%.

Approaches to Projecting Land Use Change

Any application of the above requires a baseline estimate of $CR_k(t)$. In this study, two methods are utilized to predict future land uses: (i) A Markov model of land use transition, and (ii) An econometric model of land uses (land-share model). Both models are developed based upon historical land use change data.

Markov Model of Land Use Change

The Markov model has been used to simulate and explore the dynamics of land use change. For example, Bourne used the Markov model to describe and predict land use changes inside a city, while Bell used it to investigate land use change patterns on San Juan Island, Washington. Also, Muller and Middleton used the Markov model to provide a dynamics of land use changes in Niagara area.

Data for the Markov model estimation involves historical data on AO practices adoption and can be obtained from publicly available sources such as National Resource Inventory (NRI), Census of Agriculture, or Forestry Inventory and Analysis (FIA), etc.

In the GHGE arena, several studies have used the Markov model to estimate costs of GHGE offset. Lubowski, Plantinga and Stavins use a first-order Markov model to derive a carbon sequestration supply function. They estimated the baseline land use and simulate the effects of carbon sequestration policy such as subsidies. Note that the conversion probability is set to the function of some explanatory variables and simulated to find carbon sequestration supply function. Murray uses the Markov model in Mississippi using 1982 to 1997 data and he finds the baseline conversion rate of cropland to forest is 0.67% a year.

The Markov model is attractive because it can be used easily to predict future land use change. However, model applicability is limited because pre-existing AO practices adoption data are generally available only at high levels of aggregation such as nation, region, and/or state (Murray).

Table 2 contains a Markov land transition matrix where the data in the table depict the net flows of land between and within land uses. Namely, the data in the table, A_{ij} gives the acres of land that in the prior period was in land use *i* that by the end of the period converts to land use *j*. Note that reading across the *i*th row we find the acres that were converted to another use between observations except in column *i* shows the acres that remain in the original use. The data in the *j*th column give the acres that end up in the *j*th use at the end of the period. The data in Table 2, can be used to obtain a Markov probabilistic transition matrix by computing:

$$(14) \qquad PR_{ij} = \frac{A_{ij}}{\sum_{j} A_{ij}}$$

where, PR_{ij} gives the probability that land beginning in use *i* will end up in use *j*.

Table 2. Example of Land Transition Matrix of Land Use for 1992 – 1997

			To	j		
		Crop	Forest	Pasture	Other	1992 total
From	Crop	A_{CC}	A_{CF}	A_{CP}	A_{CO}	$\Sigma_j A_{Cj}$
I	Forest	A_{FC}	A_{FF}	A_{FP}	A_{FO}	$\Sigma_j A_{Fj}$
	Pasture	A_{PC}	A_{PF}	A_{PP}	A_{PO}	$\Sigma_j A_{Pj}$
	Other	A_{OC}	A_{OF}	A_{OP}	A_{OO}	$\Sigma_j A_{Oj}$
	1997 total	$\Sigma_i A_{iC}$	$\Sigma_i A_{iF}$	$\Sigma_i A_{iP}$	$\Sigma_i A_{iO}$	

Note: A_{ij} is acres that land use i is converted to land use j. Reading to the right or left of this number are the acres that were lost to another use by 1997, and reading up or down from this number are the acres that were gained from another use by 1997.

The full Markov transition matrix associated with Table 2 is that given in Table 3. As defined above this matrix gives the transition during a time period. Such a period may involve multiple years (5 years here) and our framework requires the annual transition rate.

In order to find annual transition rate, we need to develop one-step or one-year transition probability matrix from multiple-step or multiple-year transition matrix. The n-step transition probability matrix can be obtained by computing the *n*th power of the one-step transition probability matrix (Chapter 15 in Hiller and Lieberman). The matrix of n-step transition probabilities, $\mathbf{M}^{(n)}$, can be obtained from the expression:

$$\mathbf{M}^{(n)} = \mathbf{M} \cdot \mathbf{M} \cdots \mathbf{M} = \mathbf{M}^{n} \tag{15}$$

where, $\mathbf{M}$ is the one-step transition probability matrix.

Table 3. Example of Markov Transition Matrix of Land Use for 1992 – 1997

		To		**j**		
		Crop	Forest	Pasture	Other	1992 total
From	Crop	PR_{CC}	PR_{CF}	PR_{CP}	PR_{CO}	1.0
I	Forest	PR_{FC}	PR_{FF}	PR_{FP}	PR_{FO}	1.0
	Pasture	PR_{PC}	PR_{PF}	PR_{PP}	PR_{PO}	1.0
	Other	PR_{OC}	PR_{OF}	PR_{OP}	PR_{OO}	1.0

Note: P_{ij} is the probability that land use i is converted to land use j. Reading to the right or left of this number are the probability that were lost to another use by 1997, and reading up or down from this number are the probability that were gained from another use by 1997.

The one-step transition probability matrix can be found using the nth roots of n-step Markov transition matrix and can be found with numerical program such as GAMS by minimizing the deviations between the fifth power of a matrix and the observed 5-year transition.

Once we find the one-step transition probability matrix, then annual conversion rates for land use i to j, CR_{ij}, can be constructed as:

$$(16) \qquad CR_{ij} = PR_{ij}$$

where, CR_{ij} is the annual proportional land conversion rate from use i to use j, and PR_{ij} is the (i, j) element in the one-step transition probability matrix, **M**. In turn, given the conversion rate data, the additionality discount can be found using above equations.

Econometric Model of Land Uses

An econometric approach employing the, so-called, land use share model can be used to provide a baseline prediction of the land use change rate. Land use share models have been widely used for various purposes in the past by, for example, Lichtenberg; Stavins and Jaffe; Wu and Segerson; Hardie and Parks; Miller and Plantinga; Ahn, Plantinga and Alig; and Plantinga and Wu.

The key hypothesis behind the land use share model is that land use patterns are determined by relative rents and land characteristics such as location and soil fertility (Miller and Plantinga). The most common approach is to specify the county land use shares as a function of explanatory variables that include land rents from alternative uses, relevant policy variables, and land quality measures. Following section include mathematical formation of land-share model.

Land-Share Model

We assume that land manager m_j ($m_j = 1, 2, \ldots, M_j$) in region j ($j = 1, 2, \ldots, J$) maximizes expected profits from use k ($k = 1, 2, \ldots, K$). The profit function is denoted $\pi_k(x(t, m_j), a_k(t, m_j), m_j)$ where $x(t, m_j)$ is a vector of exogenous prices, costs and other economic variables, $a_k(t, m_j)$ is the area of land of quality l devoted to use k, at time t.

For each land quality type, assume the land manager selects the area of land allocated to each use $a_k(t, m_j) \geq 0$ to maximize total profits for each q where profits are given by (Wu and Segerson; Miller and Plantinga):

$$(17) \qquad \sum_k \pi_k(x(t,m_j), a_k(t,m_j), m_j)$$

subject to

$$(18) \qquad \sum_k a_k(t,m_j) = A(t,m_j)$$

where, $A(t, m_j)$ is the total available area of land.

The Kuhn–Tucker solution to equations (17) and (18) is the optimal allocation $a_k^*(x(t,m_j), A(t,m_j), m_j)$, and the optimal share of total land $A(t,m_j) = \sum_j A_j(t,m_j)$ allocate to use k is:

$$(19) \qquad f_k(X(t,m_j), t, m_j) = \frac{1}{A(t,m_j)} \sum_j a_k^*(x(t,m_j), A(t,m_j), m_j).$$

Given that the optimal shares are implicitly determined by land quality factors embedded in the profit functions, we denote each f_k as a function of the $X(t, m_j)$ which includes the economic decision variables as well as composite measures of land quality.

In practice, the actual share of land allocated to use k by land manager m_j,

$$(20) \qquad s_k(t,m_j) = f_k(X(t,m_j),t,m_j) + u_k(t,m_j)$$

may differ from the optimal share due to exogenous shocks that occur after land use decisions have been made[2]. Thus, we need to incorporate an error term, $u_k(t,m_j)$, in equation (20). We will assume that the errors exhibit mean zero disturbances and that they are contemporaneously correlated across uses and may be correlated across time and regions. Also we assume that the errors are uncorrelated with the decision variables. Given that the actual and optimal shares sum to one, and the error term sum to zero, that is, $\sum_k u_k(t,m_j) = 0$.

Individual-specific observations of land use are not widely available, but data on aggregate land use are published[3]. The observed share of land allocated to use k in region (county) j may be assembled as:

$$\begin{aligned}(21) \qquad y_k(t,j) &= \sum_{m_j=1}^{M_j} w(t,m_j)[s_k(t,m_j) + v_k(t,m_j)] + \bar{v}_k(t) \\ &= p_k(t,j) + \varepsilon_k(t,j)\end{aligned}$$

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[2] For example, poor weather

[3] Data on aggregate land use are published by federal and state agencies. In general, the aggregate land statistics are compiled from census or survey of individual allocation decisions.

If the statistics are based on a complete enumeration of the population, $w(t, m_j)$ is the relative share of land in region j that is managed by individual m_j, and $v_k(t, m_j)$ is the potential sampling error associated with each observation. If the data are compiled through a sample survey, $w(t, m_j)$ represents the sample weight assigned to individual m_j and $\bar{v}_k(t)$ is the aggregate sampling error. The composite error term $\varepsilon(t, j)$ is a random K vector with a mean-variance structure similar to that of $u(t, j)$.

With respect to the sampling distribution of the aggregate data, we interpret $p_k(t, j)$ as the expected share of land in region j allocated to use k at time t. By substitution of equation (20) into equation (21), we can see that $p_k(t, j)$ is a function of the complete set of economic decision variables and land quality factors[4].

The expected shares are typically estimated by a censored regression approach following the qualitative choice literature because $p_k(t, j)$ is between zero to one (Ben-Akiva, and Lerman) where the logistic transformation as follows is common:

$$(22) \qquad p_k(t, j) = \frac{\exp(\beta_k' X(t, j))}{\sum_k^K \exp(\beta_k' X(t, j))}$$

where, β_k is a vector of parameters.

---

[4] As Miller and Plantinga discuss, individual-specific information is rarely available and researchers often employ county-level averages $X(t, j)$, which may include relevant proxy variables for the land quality characteristics of the county.

Equation (22) can be modified by taking the logarithm of the observed shares and normalizing on $y_1(t, j)$ (Judge *et al.*):

$$(23) \qquad \ln(y_k(t, j) / y_1(t, j)) = \beta_k' X(t, j) - \beta_1' X(t, j)$$

where, $y_k(t, j)$ is the observed land shares in region j in time t as discussed above. The parameters are normalized by setting $\beta_1' = 0$ and can be consistently estimated by least squares[5].

Estimation of Land Conversion Rate

From equation (23), estimates of the conversion rate, CR_{kj} can be obtained from the model coefficients because total differentiation of equation (23) indicates that the model coefficients measure the percentage change in the share ratios for a one-unit change in the independent variables. In other words, everything else constant, a one-unit change in the projected area explanatory variable increases or decreases the ratio of other crop or forestland by estimated coefficients (Ahn, Plantinga, and Alig).

This approach is attractive because statistical tests are possible and landowners' behavior can be explained with economic theory. Also we estimate β_k, then we can calculate the percent change in land share for the future and examine conversion rate. However, there is need to find the future values of the explanatory variables. Also, the

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[5] The number of relevant economic and land quality variables may be larger than the available sample size, and unique estimates of county-specific model parameters cannot be computed by least squares. In such cases, researchers combine data for many counties and estimate a pooled regression model with cross-county parameter restrictions (Miller and Plantinga).

projected area assumed to be converted to other land uses in a proportional fashion regardless of stock level and this assumption may be unrealistic.

Concluding Remarks

AO offsets need to be additional to the baseline. In an AO project, additionality is concerned when the region where a project is being proposed has had substantial adoption of the AO practice before any GHG programs were implemented, and this adoption is expected to continue. In such a case, a discount for the region may need to reflect business-as-usual AO practice adoption.

Estimate of the additionality discount is important because the credit buyers and the government agency or regulatory agency assure the GHGE credits paid for are in fact additional. When the additionality discount is positive, the claimable GHGE credit would decrease.

In order to estimate the additionality discount, we need to investigate individual producer's profit structure and in turn, marginal cost schedule for offsetting GHGE. Also, we need to have information for producer's type but there exists an asymmetric information problem that will cause some biases when we measure the additionality discount. The asymmetric information problem cannot be overcome at a reasonable cost.

We propose a *project-based approach*, that is, we assume that all of producers in the region adopt the AO project when the GHGE credit price is greater than equal to their marginal cost. Based on the distribution of producer type we can project the

GHGE offset. In this case, we need estimates of land use transitions to compute baseline GHGE offset. For doing this, we can utilize the Markov transition matrix and/or an econometric approach in the form of the land share model.

CHAPTER IV

ESTIMATE OF LEAKAGE DISCOUNT

Background

When an AO project succeeds, it potentially reduces the supply of agricultural production on the project area. In the competitive agricultural markets are likely that additional supply will arise from production outside of the project area, with accompanied increasing GHGE. To the extent that this happens, the AO project based GHG offset *leaks*.

In other words, actions to reduce net GHGE may alter current or anticipated production levels; in turn creating alterations in market conditions (e.g. price effects) that can induce emission increases elsewhere (Murray, McCarl and Lee). Because agricultural markets are highly competitive and demand curve is relatively inelastic, leakage effects may be substantial. In this case, the GHG offset gains for which one can claim credits should be discounted by the amount of leakage.

For example, suppose that in a region a significant amount of cropland is converted into pasturelands in the name of an AO program. In turn, that conversion would lower production and raise prices stimulating producers in other regions to try to meet the associated market shortage. That reaction could involve developing croplands from pasturelands, forestlands or wetlands all of which would cause additional GHGE.

Empirical studies on leakage can be found in the economics literature on investment crowding or slippage effects in agricultural conservation programs or U.S. crop commodity programs. Lee, Kaiser and Alig examine U.S. tree planting programs and support a crowding-out effects for government subsidized tree planting versus private tree planting. Wu examines the Conservation Reserve Program (CRP), and finds that about 20% of the acres diverted from production were replaced by other acreage with 9 to 14% of the environmental benefits offset. Brooks, Aradhyula and Johnson and Hoag, Babcock and Foster investigate the leakage effect in U.S. crop commodity programs and provide evidence of offsetting responses by producers.

Regarding afforestation policy, Murray, McCarl and Lee estimate that the leakage would be 43% to 58% under a policy for federal timber restrictions to sequester carbon in the U.S. Pacific-Northwest area. And they show that leakage can be estimated by a formula involving market parameters such as price elasticities, and market shares. Lee *et al*. (2000) shows unilateral U.S. implementation of an agriculturally based GHGE offset program leads to a decline in U.S. agricultural exports and an increase in production in the rest of the world, which is indicative of leakage.

The purpose of this chapter is to further examine the concept of leakage in an economic sense and develop an economic measure of leakage.

Graphical Analysis and Justification for Leakage

Leakage occurs to the extent that the GHGE saved in a project area is offset by a market driven increase in GHGE outside of the project area. The project area is the area where the AO project is put into effect, and the outside area is the rest of the world. When the AO project causes project area production to fall then the total supply of output will decrease. In turn this causes output price to rise under a *ceteris paribus* assumption.

This rise in output price stimulates producers outside the project area to increase output. When additional net GHGE outside of the project area are zero then there is no leakage effect and when the added GHGE is the same as that in the project area, there is a 100% leakage effect.

Suppose that there are two identical regions that produce crops. In other words, there are two crop suppliers in the market:

$$(24) \qquad S_{Proj} = S_{Proj}(P_C, W_{Proj})$$

$$(25) \qquad S_{Out} = S_{Out}(P_C, W_{Out})$$

where, the subscript *Proj* represents production in the "Project Area" which is targeted by the AO program and the subscript *Out* represents production "Outside of the project area". S_{Proj} and S_{Out} give the quantity of the crop supplied by the two parties while P_C gives the price of the crop and *W* the input price vector.

Now assume the aggregate demand function for the crop is:

$$(26) \qquad D = D(P_C, Z)$$

where, *D* is the quantity of crops consumed, and *Z* is a vector of demand shifters such as income and prices of substitute commodities. Market equilibrium equates supply and demand:

$$(27) \qquad S_{Proj}(P_C^*, W_{Proj}) + S_{Out}(P_C^*, W_{Out}) = D(P_C^*, Z)$$

where equilibrium crop price is P_C^*.

It is helpful to derive the excess demand for supply facing area *Out*, which is the difference between total demand and the supply by area *Proj*. The excess demand for area *Out* can be defined as follows[6]:

$$(28) \qquad ED(P_C, Z, W_{Proj}) = D(P, Z) - S_{Proj}(P, W_{Proj})$$

Inserting equation (28) into the equilibrium condition in equation (27), then the equilibrium for area *Out* can be found:

$$(29) \qquad S_{Out}(P_C^*, W_{Out}) = ED(P_C^*, Z, W_{Proj})$$

Such a market is illustrated in Figure 4 where the excess demand function for area *Out*, ED^0, is the difference between the total demand function *D* in panel (a) and the supply function S_{Proj}^0 in panel (b). The equilibrium price is P_C^0, the amount produced in area *Out* is Q_{Out}^0, in area *Proj* is Q_{Proj}^0, and the total amount produced and consumed is $Q^0 = Q_{Out}^0 + Q_{Proj}^0$. Correspondingly, the land usage for crop cultivation in area *Out* is L_{Out}^0 and in area *Proj* is L_{Proj}^0 from the production function in Panel (d) and (e). Total land usage is $L^0 = L_{Out}^0 + L_{Proj}^0$.

Suppose that the AO program makes producers discontinue crop cultivation and plant trees through afforestation. In such a case, supply from the project area *Proj* will decrease (to zero) as shown in panel (b) in Figure 4, and the excess demand faced by producers in area *Out* rises.

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[6] The idea of the excess demand is introduced here based on Murray, McCarl and Lee.

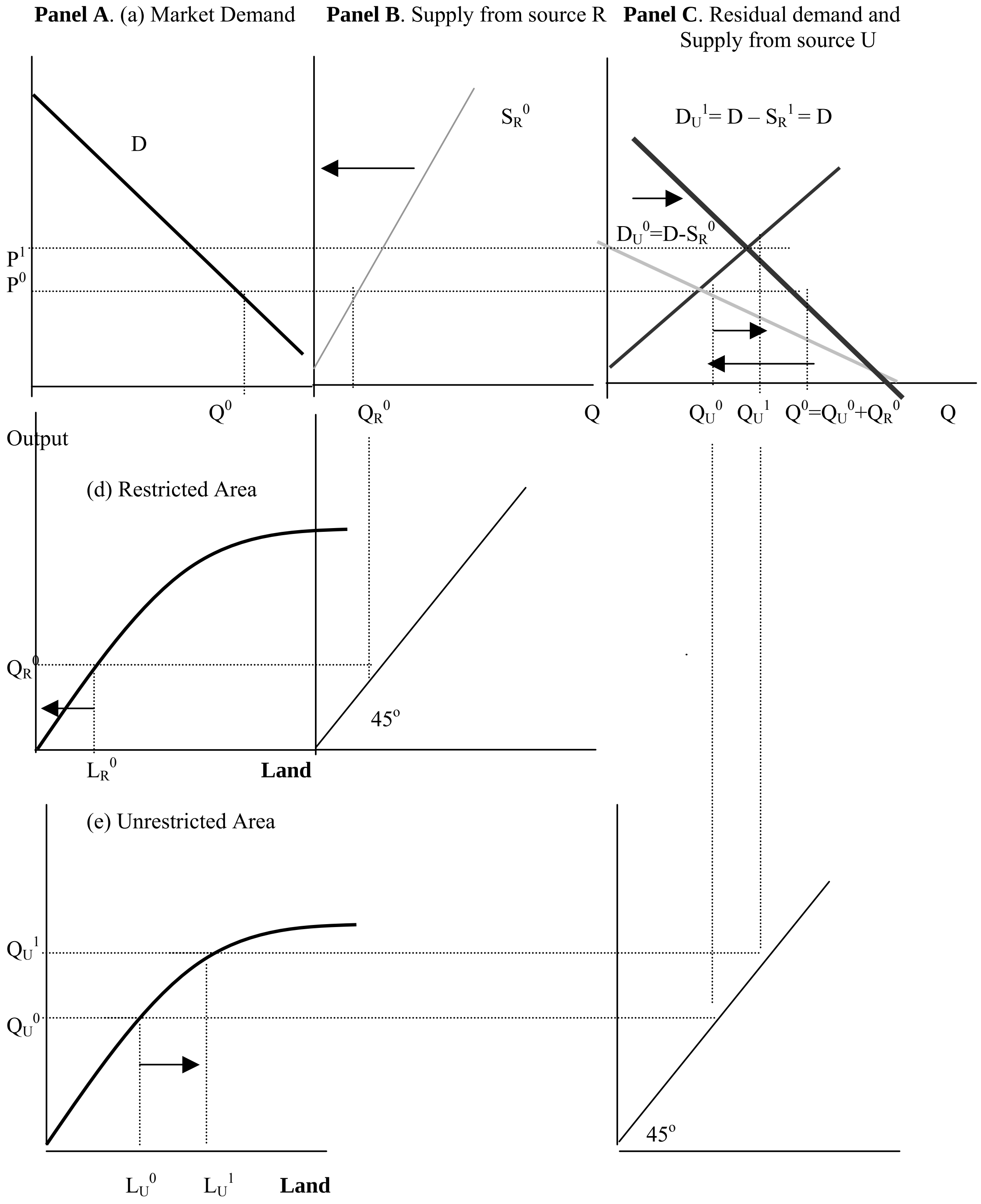
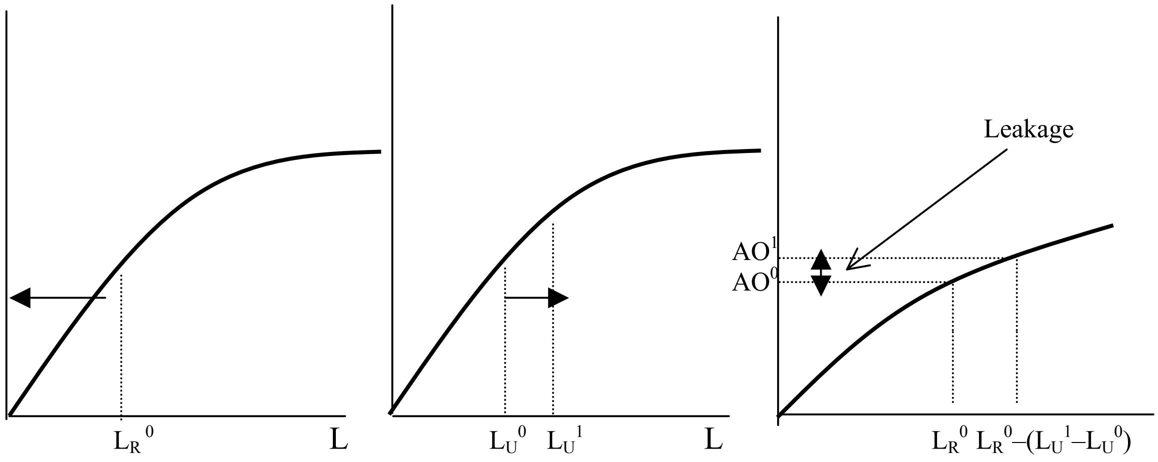


Figure 4. Output market and land use change

This is illustrated in Figure 4 by a rightward shift in *Out*'s excess demand function from ED^0 to ED^1 or *D*. The demand shift causes producers' response which could increase emissions and thus offset part of project gains illustrates the leakage effect.

The rightward shift in *Out*'s demand function disrupts the initial price/quantity equilibrium. In order for the market to clear again, the output price will rise and will induce more supply into the market from additional production in the non-project area.

The new equilibrium is reached at (P_C^1, Q^1) and $Q^1 = Q_{Out}^1$. The supply from the area *Out* expands from Q_{Out}^0 to Q_{Out}^1. At the new equilibrium, the land usage in area *Out* is L_{Out}^1. The increase in land allocation raises the potential for leakage by the price-induced supply response.



Panel A. Restricted area **Panel B**. Unrestricted area **Panel C**. GHGE Offset

Figure 5. GHGE offset and leakage effects

The leakage effect under the assumption of equal emissions per acre is illustrated in Figure 5. The GHGE offset in the project area is AO^0 but the increase in land usage in the unrestricted area increases their GHGE offset by AO^1. The leakage can be defined as the distance between AO^0 and AO^1 in Figure 5.

Derivation of Leakage Discount

In this section, a formula for a leakage discount (*LEAK*) is derived. Most of development is similar to that in Murray, McCarl and Lee. However, there are two important differences: (i) the leakage discount developed here is for leakage in terms of input usage change (especially land) not output change so that we need one more parameter giving the change in output per unit change in inputs (we will call it the input elasticity from now on), E_{input}, and (ii) the leakage discount developed here considers land conversion into multiple alternate uses and the accompanying leakage from multiple sources.

Leakage in Single Land Use

Conceptually, the leakage discount can be defined as follows:

$$(30) \qquad LEAK(\%) = \frac{\Delta L_{Out} \cdot SR_{Out}}{L^0_{Proj} \cdot SR_{Proj}} \times 100$$

where, ΔL_{Out} is changes in area *Out*'s land allocation to crop, which is defined as $\Delta L_{Out} = L^1_{Out} - L^0_{Out}$ and *SR* is the per acre net GHGE offset rate in area *i*, and L^0_{Proj} is the project area. The denominator can be interpreted as the total amount of GHGE offset by the AO project in the *Proj* area, (that is, *Q* in equation (1) in Chapter II) and the numerator is the amount of GHGE leaked outside of the project area (that is, $Q - Q_C$ in equation (1) in Chapter II).

If net AO offset rates (SR) are the same in each area, the leakage can be expressed by the ratio of the changes in land use ΔL_{Out} to L^0_{Proj} but this is likely not the case. Thus to estimate the leakage discount, we need to predict or measure ΔL_{Out}, SR_{Out}, and SR_{Proj}, and with known L^0_{Proj} that is the size of the project area.

Suppose the input elasticity with respect to land is E_{input}, which is defined as follows:

$$(31) \qquad E_{input} \equiv \frac{\Delta Q^S}{\Delta L} \cdot \frac{L^0}{Q^0}$$

where, ΔQ^S is the changes in quantities supplied. Then using equation (31), ΔL_{Out}, can be found as follows:

$$(32) \qquad \Delta L_{Out} = \frac{1}{E_{input}} \cdot \frac{\Delta Q^S_{Out}}{Q^0_{Out}} L^0_{Out}$$

Initial supply from area *Out*, Q^0_{Out}, initial land use, L^0_{Out}, and the input elasticity for land, E_{input}, are observable but ΔQ^S_{Out}. This supply change can be found in the market. The change in excess demand for the producers in the area *Out* can be expressed as follows:

$$(33) \qquad \Delta ED = Q^0_{Proj} + E_D (Q^0_{Out} + Q^0_{Proj}) \frac{\Delta P_C}{P_C}$$

where, ΔED is the change in excess demand facing area *Out*, Q^0_{Proj} is the baseline market quantity of area *Proj*, E_D is the price elasticity of demand, and P_C is the market price. The first term on the right hand side reflects the outward shift in *Out*'s demand given the removal of supply from area *Proj*, and the second term reflects how consumers respond to the market price change.

If we introduce a *scale parameter* which is defined as $\phi = Q^0_{Proj} / Q^0_{Out}$ to remove Q^0_{Proj} from equation (33), then equation (33) would be modified as follows:

$$(34) \qquad \Delta ED = E_{input}\phi Q^0_{Out} + E_D(1 + E_{input}\phi)Q^0_{Out}\frac{\Delta P_C}{P_C}$$

where, Q^0_{Out} is the baseline market quantity of area *Out*, ϕ is the scale parameter and E_{Input} is the input elasticity of land changes.

The changes in supply by producers in the area *Out* is,

$$(35) \qquad \Delta Q^S_{Out} = E_S Q^0_{Out}\frac{\Delta P_C}{P_C}$$

where, E_S is the price elasticity of supply.

Setting equations (34) and (35) equal to each other and solving for the proportional change in the equilibrium price gives:

$$(36) \qquad \frac{\Delta P_C}{P_C} = \frac{E_{Input}\phi}{E_S - E_D(1 + E_{Input}\phi)}$$

Substituting equation (36) into equation (35) yields:

$$(37) \qquad \Delta Q_{Out}^{S} = \frac{E_{Input} E_S \phi Q_{Out}^{S}}{E_S - E_D (1 + E_{Input} \phi)}$$

And substituting equation (37) into equation (32) yields:

$$(38) \qquad \Delta L_{Out} = \frac{E_S \phi}{E_S - E_D (1 + E_{Input} \phi)} L_{Out}^{0}$$

Using equation (38), the leakage discount can be found as a function of exogenous parameters as follows:

$$(39) \qquad LEAK(\%) = \frac{\Delta L_{Out} \cdot SR_{Out}}{L_{Proj}^{0} \cdot SR_{Proj}} \times 100 = \frac{E_S \phi}{E_S - E_D (1 + E_{Input} \phi)} \cdot \frac{L_{Out}^{0} \cdot SR_{Out}}{L_{Proj}^{0} \cdot SR_{Proj}} \times 100$$

Based on equation (39), the leakage effect depends on the supply and demand price elasticities and the input elasticity of the land. All else held constant, the leakage effect decreases when supply is more inelastic, and the leakage effect increases when demand is more inelastic. Leakage increases when the input elasticity is more inelastic and decreases when the supply responsiveness to the land is more elastic. Inelastic input elasticity implies that more land is needed to produce the same output.

Leakage in a Multi-Land Use Context

Leakage may occur through more than one market, ΔL_{Out}, can involve land conversions in a number of different land uses such as conversion from croplands into pasture or forestry. For example, we could convert a significant amount of croplands into forestlands in one region in the name of the AO project. In turn, that conversion would lower production and raise crop prices but lower timber prices stimulating producers in other regions nationally or internationally to try to adjust to altered market prices. Note that reactions in terms of croplands, grasslands, and forests lands involve different offset rates. That is to say, the net AO offset rate in area *Out*, SR_{Out}, in equation (39) should be decomposed in order to consider these differences.

To do this, there is need to predict land use change, and it can be done with a Markov model. The Markov model can be used to find conversion rate from one land use to another land use (See Chapter III for more details). In the case of leakage, the conversion rate may be increased due to rises in output price. However, we assume that conversion rate is constant. In turn that conversion rate can be used as a weight to find the leakage effect. In other words, equation (38) can be modified as follows:

$$(40) \qquad LEAK(\%) = \left(\sum_{k=1}^{K} \frac{E_S \phi L_{Out}^0}{E_S - E_D(1 + E_{Input}\phi)} \frac{CR_{kOut}}{CR_{Out}} \cdot SR_{kOut} \right) \frac{1}{L_{Proj}^0 \cdot SR_{Proj}} \times 100$$

where, *k* depicts each source such as other croplands, pastureland or forests lands, SR_{kOut} is the sequestration rate of alternative *k*, CR_{kOut} is the (absolute value of) conversion rate from or to the *k* alternative and CR_{Out} is the total conversion rate that is defined as

$CR_{Out} = \sum_{t=1}^{K} CR_{kOut}$ and *SR* the net emission rate.

Concluding Remarks

When an AO project succeeds in one region, it potentially reduces regional production of agricultural products. Markets may react by encouraging additional production and

GHGE in other regions, thereby offsetting the net reduction in GHGE. To the extent that this happens, the AO project-based GHGE offset leaks. In this case, the claimable GHGE offset should be reduced by the induced out of region increase in GHGE. In other words, leakage reduces the salable quantity of GHGE offset.

In this chapter, we derived the leakage discount formula as a function of exogenous market parameters including price elasticities and input elasticity. The leakage effect may be substantial because both demand and supply elasticities are typically inelastic for agricultural products. In the case of the AO project, it is important to identify the variety of land use management pattern changes elsewhere and offset consequences. In turn, we propose using weights which are calculated based on conversion rates and the net AO offset rates.

CHAPTER V

ESTIMATE OF PERMANENCE DISCOUNT

Background

An AO project, mainly involving carbon sequestration, can contribute to societal GHG mitigation, but has the characteristic that the sequestered carbon is not necessarily permanent. Namely, once the AO project is put into place, the realized soil carbon gains are stored in a volatile form and the annual rate of carbon gains are not the same over time.

In particular, the soil carbon content reaches a new equilibrium where accumulation stops (West and Post), and agricultural soil sequestration from tillage changes can be expected to peak in 5 to 10 years, reaching a new equilibrium in 15 to 20 years in the case of agricultural soil carbon sequestration (West and Post). In the forestry case, soil and standing tree carbon reach equilibrium by year 80 for un-harvested southeastern U.S. pine stands (Birdsey). Furthermore, when the AO practice is discontinued, most of carbon is released quickly to the atmosphere and the system reverts back to the pre-AO practice equilibrium (IPCC).

This situation contrasts with the case of most direct emission reductions which represent permanent removals of GHG from the atmosphere, even if the emission reductions activities are of a limited duration. Thus, saturation and volatility in the AO sequestration projects introduce additional considerations since these permanence characteristics can change the GHGE credits generated by the AO project. These considerations lead to a permanence discount. Conceptually, a permanence discount involves a comparison between permanent removals of GHG with temporal storage of GHG, which can be released (accidentally or on purpose) to the atmosphere in the future.

The following section presents more details on permanence, and volatility and develops a permanence discount. Also, it is important to consider the future value of carbon storage when we calculate the permanence discount because time horizons in equation (4) in Chapter II are different. Finally we extend the concept developing a permanence discount into the multiple GHGE offset case.

Analytical Approach for Permanence

Conceptual Permanence Discount

Suppose that a firm (or government) wants to purchase GHGE credits under an AO sequestration program. Based on the saturation year, the AO project can be divided as: (i) adoption of reduced tillage or conversion to other crops or pasturelands that is likely to saturate after 20 years and (ii) conversion to forestry (afforestation) that is likely to saturate 80 or more years.

Sequestered carbon will be released to the atmosphere in the future if the AO practice is discontinued or some disturbances such as wildfire or pest outbreaks occur. These dynamic permanence considerations imply that the comparison of sequestration methods should adjust for the time value of emissions offsets and possible future emissions. In this case, GHGE credit would be given for the number of tons of carbon held out of the atmosphere for a given number of years (Marland, Fruit, and Sedjo). This is the concept of a permanence discount.

We define the permanence discount as one minus the ratio of the benefit gained from carbon sequestration while carbon is stored compared to the benefit gained if the sequestration was permanent as pointed out in Chapter II. Here, we can use a ton-year accounting to compute permanence discounts.

Equivalence Time and Ton-Year Accounting

A ton-year accounting approach is used to compare activities that sequester (or release) carbon for different lengths of. Under a ton-year accounting carbon sequestration is valued on the basis of both the number of tons sequestered and years over which it is sequestered (Noble *et al*.). The concept of a ton-year accounting has been discussed in many studies (Fearnside, 1995, 1997; Moura-Costa, 1996; Chomitz, 1998; Tipper and de Jong).

The ton-year accounting converts the climatic effect of temporal carbon storage to an equivalent amount of (current) permanent removal of carbon (Dobes, Enting, and Maskin; Tipper and de Jong). This factor is derived from the equivalence time (*Te*) concept (Moura-Costa, 1996), that is, the length of time that CO_2 must be stored as carbon in biomass or soil for it to prevent the cumulative radiative forcing effect exerted by a similar amount of CO_2 during its residence in the atmosphere.

The equivalence time is defined as ton-years/*Te* = permanent tons. The basic question is how long carbon must be sequestered to be equivalent to permanent emission reduction (IPCC). The choice of *Te* is important because the value of sequestration is completely determined by the choice of *Te* (Herzog, Caldeira and Reilly).

Alternative methodologies have been proposed to generate this equivalence time parameter. Tipper and de Jong base their calculations on the difference between current atmospheric concentrations and the pre-industrial equilibrium concentration of CO_2 to derive a carbon storage period (*Te*) of 42–50 years following initial sequestration. Chomitz (1998) propose similar ranges 50 years. Dobes, Enting, and Maskin calculates *Te* = 150 years.

In this study, we use *Te* = 100 years. The rationale for the 100-year time horizon is based on the argument that the problem of comparing carbon storage of different lifetimes is conceptually equivalent to comparing GHG of different lifetimes. This comparison has already been addressed in the construction of Global Warming Potential (GWP), where the GHW measures adopted in the Kyoto Protocol are based on a 100-year horizon (IPCC; Fearnside; Fearnside, Lashof and Moura-Costa).

Permanence Discount Based on Ton-Year Accounting

Under the ton-year accounting system, credit would be awarded for the number of tons of carbon held out of the atmosphere for a given number of years. For example, under an assumption of constant atmospheric CO_2 burden, the certain carbon sequestration project sequesters 1 ton of CO_2 in year zero (one time sequestration) and holds it for 100 years, then this project provides 100 ton-years and gains full credits. In other words, this project is regarded as a permanent emission reduction and thus, permanence discount should be zero.

If all of the carbon sequestered in year zero is released to the atmosphere in year 50, then this project provides only 50 ton-years. This project gains only 50% of full credit and permanence discount is simply estimated as 50% (1 – 50 ton-years/100 ton-years) based on equation (1) in Chapter II.

It is noteworthy here that the effect or atmospheric CO_2 burden is not constant over time. According to Joos *et al*., the effect is decaying over time based on the carbon cycle model. Joos *et al*. give a function for this decay and denote it $F(t)$[7]. If we use this carbon burden model, sequestration of 1 ton of CO_2 in year zero with its removal for the full 100 years reduces the atmospheric CO_2 burden by $\int_0^{100} F(t)dt \approx 46.4$ ton-years (not 100 ton-years). Also if all of the carbon sequestered in year zero is released to the atmosphere in year 50, the reduction in atmospheric CO_2 burden is $\int_0^{50} F(t)dt \approx 28.2$ ton-years (not 50 ton-years). Thus, this project would gain 61% of the permanent offset and the permanence discount is simply estimated as 39% (= 1 – 28.2 ton-years/46.4 ton-years). This is illustrated in Figure 6.

Panel (A) depicts the permanent reduction of 1 ton of CO_2 for 100 years and Panel (B) depicts the carbon sequestration of 1 ton of CO_2 in year zero and followed by emission of 1 ton of CO_2 in year 50. The reduction in atmospheric burden is calculated as the area of under the curve in each Panel.

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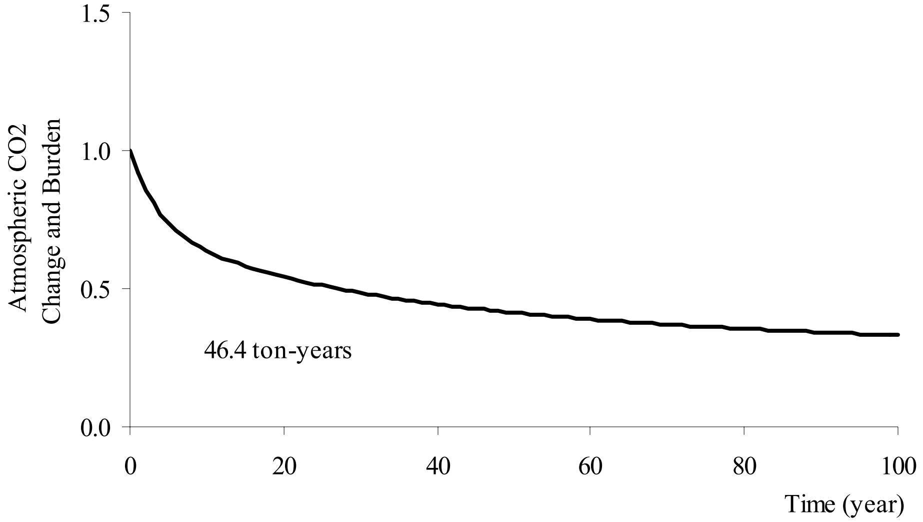
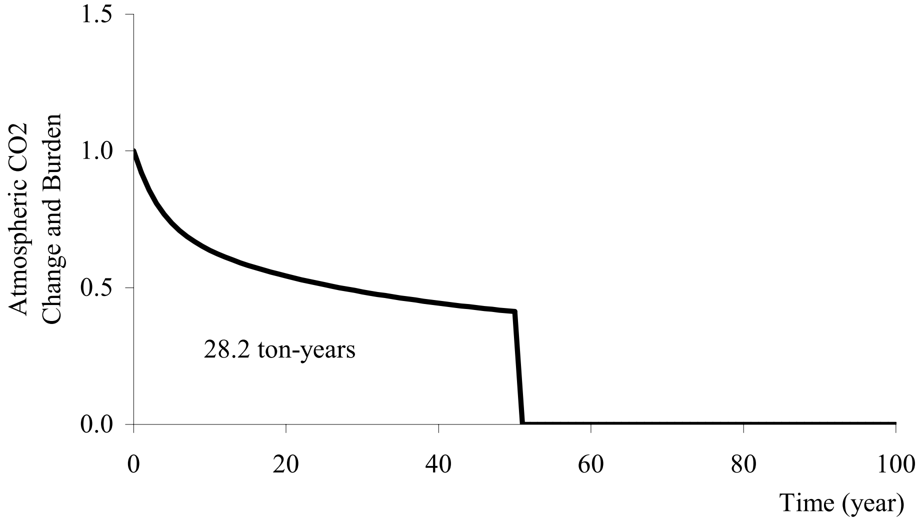
[7] $F(t) = 0.1756 + 0.1375 \exp(-t/421.09) + 0.1858 \exp(-t/70.60) + 0.2423 \exp(-t/21.42) + 0.2589 \exp(-t/3.42)$, where F is the fraction of CO_2 remaining in the atmosphere or changes in atmospheric CO_2 burden.



Panel A. Permanent reduction of 1 ton of CO_2 for 100 years



Panel B. Sequestration of 1 ton of CO_2 for 50 years and followed emission

Figure 6. Reductions in atmospheric burden from removal of 1 ton of CO_2 in year zero and followed by emission in year 50

The more interesting case is that the AO sequestration project sequesters 1 ton of CO_2 in every year until saturation after reaching equilibrium (assume that it occurs in year 50). After saturation, if this project is discontinued, then suppose the sequestered carbon is released to the atmosphere immediately (it is assumed to occur within one year).

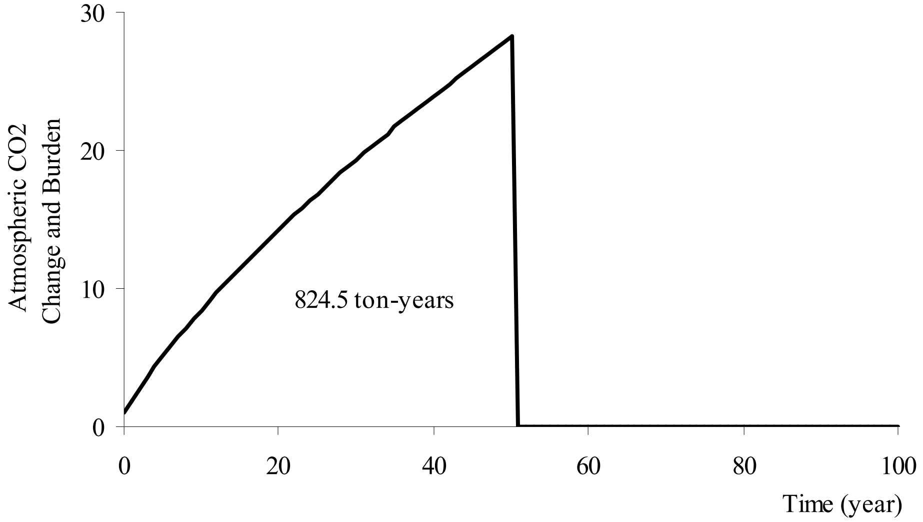
This case is illustrated in Figure 7. Panel (A) in Figure 7 shows permanent removal of 1 ton of CO_2 in the first 50 years and holds the carbon forever (100 years), and Panel (B) shows sequestration of 1 ton of CO_2 in the first 50 years and these are released to the atmosphere in year 50.

In this case, the permanent reduction reduces the atmospheric CO_2 burden by $\sum_{t=0}^{100}\left(\int_{t}^{100} F(t)dt\right) \approx 1919.4$ ton-years. On the other hand, the carbon sequestration alternative which releases the carbon in year 50 reduces atmospheric CO_2 burden by $\sum_{t=0}^{50}\left(\int_{t}^{50} F(t)dt\right) \approx 824.5$ ton-years. Thus, this project gains only 43% of the permanent offset and the permanence discount is simply estimated as 57%.

Permanence Discount Coupled with Time Value

The objective of ton-year accounting is to determine the environmental value of GHG mitigation projects based on the amount of sequestered carbon and the duration of carbon storage. Thus, the ton-year accounting does not have economic considerations in it. However, because GHGE reductions in the future are not worth the same as equal reductions are today, a calculation of permanence discount should be made under the economic considerations (Richards; Herzog, Caldeira, and Reilly; Moura-Costa, 2002; Ferarnside, Lashof, and Moura-Costa).

Panel A. Permanent reduction



Panel B. Sequestration

Figure 7. Reductions in atmospheric CO_2 burden from 50-year sequestration and followed by emissions of all in year 50

The rationale for an economic approach is discussed in Chapter I and Chapter II. When a buyer forms a long-run investment portfolio, the AO project will be compared with other mitigation options and this implies that consideration of explicit carbon price (path) and interest rate is important because time horizons in equation (5) in Chapter II are different[8].

Suppose that we calculate the permanence discount based on the net present value (*NPV*) concept. In that case the *NPV* of benefits of a permanent carbon reduction is:

$$(41) \qquad NPV^{PM} = \sum_{t=0}^{100} \left(\int_{t}^{100} e^{-rt} P(t) Q(t) F(t) dt \right)$$

where, *P*(*t*) is the carbon price in time *t*, *Q*(*t*) is the quantity of sequestered carbon in time *t*, *r* is the appropriate interest rate. Note that the superscript *PM* indicates permanent GHGE reduction. Also, we define the *NPV* of the benefits from a carbon sequestration followed emission in year *ST*:

$$(42) \qquad NPV^{TM} = \sum_{t=0}^{ST} \left(\int_{t}^{ST} e^{-rt} P(t) Q(t) F(t) dt \right)$$

where, the superscript *TM* indicates temporal GHGE storage. From equations (41) and (42), we can define the permanence discount (*PERM*) as follows:

$$(43) \qquad PERM(\%) = \left(1 - \frac{NPV^{TM}}{NPV^{PM}} \right) \times 100 .$$

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[8] Recall equation (5) in Chapter II: $\delta(\%) = \left(1 - \frac{NPV^{1}}{NPV^{0}}\right) \times 100$.

Suppose that there is a carbon sequestration project with a duration 50 years exemplified above section. Assume that carbon price is \$1/ton and constant over time for simplicity and the interest rate is 4%. The permanence discount in this case can be found using equation (43). Note that we assume that $Q(t)$ = 1 ton of CO_2:

$$\left(1-\frac{\sum_{t=0}^{50}\left(\int_{t}^{50} e^{-0.04t}F(t)dt\right)}{\sum_{t=0}^{100}\left(\int_{t}^{100} e^{-0.04t}F(t)dt\right)}\right)\times 100 \approx \left(1-\frac{266.8}{337.1}\right)\times 100 = 21\% .$$

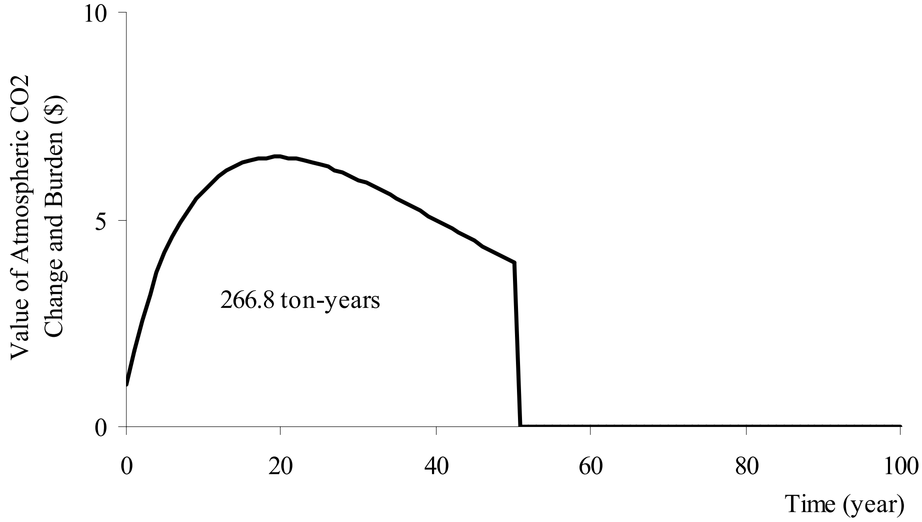
Thus, *PERM* is 21% and thus, this project should be given 79% of the full credit. This is illustrated in Figure 8.

Empirical Permanence Discounts for Alternative Projects

In order to estimate the empirical magnitude of *PERM* discounts for alternative AO projects, we need additional assumptions. Assume the following:

- Quantity of GHGE offset, $Q(t)$, equals 1 ton of CO_2 per year until saturation, and zero thereafter,
- Carbon price, $P(t)$, is \$1/ton and constant over time,
- Time horizon, Te, is 100 years,
- When the AO project is discontinued, all of CO_2 are released to the atmosphere within 1 year, and
- Interest rate is 4%.

Panel A. Permanent reduction



Panel B. Sequestration

Figure 8. Change in value of atmospheric CO_2 burden from 50-year sequestration and followed by emissions of all in year 50 when carbon price is $1/ton

Agricultural Soil Offset

Consider an agricultural soil offset that sequesters carbon from the atmosphere for the first 20 years and zero thereafter. Agricultural producers are paid to adopt the AO practice for 20 years, but there are two possibilities beyond year 20.

Case A1 is that producers revert back to previous crop cultivation after saturation occurs. Subsequently, the sequestered carbon volatilizes to the atmosphere immediately. This is a carbon sequestration project with a duration 20 years. In this case, *PERM* is calculated as 52.2% using equation (42).

Case A2 is that producers maintain the AO project because of GHG payment keeping for full 100 years or their own best interest without GHG payment. In such a case, producers hold sequestered carbon for 100 years (no volatility problem) and in turn, *PERM* is zero. All of sequestered carbon would be given a credit (See Table 4).

Afforestation

In the case of afforestation, volatility occurs when lands revert to agricultural use after harvest or much of aboveground and belowground carbon is removed in the harvesting process. The permanence discount calculation for afforestation is more complicated than agricultural soil offset because there is a need to include (i) timing of forest harvest (rotation type: shorter rotation or longer rotation), and (ii) whether reforestation occurs after harvest. The time to saturation (80 years) and post harvest carbon profiles are based on Birdsey data for southeastern U.S. pine plantations. We consider 6 cases, F1 through F6. Assume that all of carbon stored in wood volatilizes immediately.

Table 4. Agricultural Soil Offset and Permanence Discounts

Cases	Saturation Year (*ST*)	Practice After Saturation	PERM Discount (%)
A1	20	Revert	52.2
A2	20	Maintain	0.0

Cases F1 and F2 depict a forest kept to saturation. Under case F1, there is no harvest and the stand is kept forever so that there is no possibility for reforestation and volatility. Under case F2, there is harvest at year 80 but reforestation is not done. Cases F3 and F4 are for shorter rotation forestry primarily managed for pulpwood, which are harvested at year 20. Case F3 permits no reforestation after harvest, and case F4 allows reforestation after harvest. Cases F5 and F6 are for longer rotation forestry primarily managed for saw timber, which are harvested at year 50. Case F5 prohibits reforestation after harvest but case F6 allows reforestation after harvest.

When reforestation is not allowed, we utilize equation (43) directly to compute the permanence discount. However, we need to modify the NPV^{TM} in equation (43) to reflect re-accumulation of carbon when reforestation is allowed. The NPV^{TM} is expanded to consider carbon re-accumulation after reforestation as follows:

$$(44) \qquad NPV_R^{TM} = \sum_{n=1}^{N} \left(\sum_{t=0}^{RY_n} \int_t^{RY_n} e^{-rt} P(t) Q(t) F(t) dt \right),$$

where, RY_n is nth rotation or harvest year and subscript R indicates reforestation.

Thus, *PERM* is re-defined when reforestation is allowed:

$$(45) \qquad PERM(\%) = \left(1 - \frac{NPV_R^{TM}}{NPV^{PM}}\right) \times 100 .$$

This can be illustrated using Figure 9, which depicts the case of F4. Case F4 is for shorter rotation forestry harvested at year 20 and allows reforestation after harvest. When afforestation is adopted, carbon is accumulated in the first 20 years at decreasing rate. As assumed above, $Q(t)$ = 1 ton of CO_2 and $P(t)$ = \$1/ton. In year 20, most of the carbon sequestered is released to the atmosphere but carbon begins to accumulate again due to reforestation. This is illustrated by increases in carbon accumulation after year 20. In such a case, the reduction atmospheric CO_2 burden is calculated by

$$\begin{aligned} NPV_R^{TM} &= \sum_{t=0}^{20} \int_t^{20} e^{-0.04t} F(t)dt + \sum_{t=20}^{40} \int_t^{40} e^{-rt} F(t)dt + \sum_{t=40}^{60} \int_t^{60} e^{-rt} F(t)dt + \\ &\sum_{t=60}^{80} \int_t^{80} e^{-rt} F(t)dt + \sum_{t=80}^{100} \int_t^{100} e^{-rt} F(t)dt \approx 199.4 \end{aligned}$$

Based on above discussion, the permanence discounts for afforestation are estimated as follows. Under F1, *PERM* is zero because sequestered carbon is not released during 100 years. The salable GHGE offset can be given full credits. Under case F2, there is harvest at year 80 but reforestation is not allowed then *PERM* is computed as 5.7%. Cases F3 and F4 are harvested at year 20. Case F3 permits no reforestation after harvest. In this case, *PERM* is 52.2%. Case F4 allows reforestation after harvest and *PERM* decreases to 29.5%. Cases F5 and F6 are harvested at year 50. Case F5 prohibits reforestation after harvest. In this case, *PERM* is 20.8%. Case F6 allows reforestation after harvest and *PERM* is 16.4% (See Table 5).

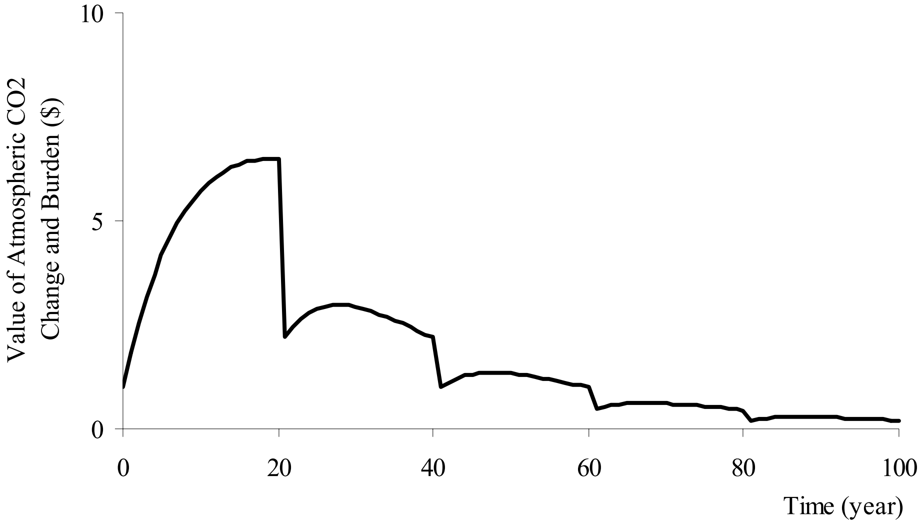


Figure 9. Change in value of atmospheric CO_2 burden from F4 project

As shown in Table 5, all of permanence discounts are positive when volatility occurs, and it implies that salable GHGE offsets decrease. It is noteworthy that shorter rotation forestry management option has the larger permanence discounts. Also, if volatility does not occur because the AO project is kept maintaining and holding carbon, then *PERM* would be zero and producers will be able to claim full credits.

Permanence Discount under Multiple GHGE Offset

The above discussion is limited to carbon sequestration while the AO project could also involve other GHGE offsets such as reductions in emission of CO_2, methane (CH_4) and nitrous oxide (N_2O). For example, reducing rice cultivation in favor of tree planting also reduces emissions of CH_4 to the atmosphere[9].

Thus, an AO project which converts rice lands to other croplands or forestlands should consider saved CH_4 emissions. Also, when producers adopt no-till as the AO project, they can reduce fuel usage for machinery so that CO_2 can be saved. Note that theses emissions reductions are permanent. Thus, Q by the AO project can be decomposed into two components as follows:

$$(46) \qquad Q(t) = CE(t) + OE(t)\,,$$

Table 5. Afforestation and Permanence Discounts

Cases		Saturation Year	Harvest Age	Reforest after Harvest	PERM Discount (%)
F1	Forest kept	80	Never		0.0
F2	to saturation	80	80	No	5.7
F3	Shorter	80	20	No	52.2
F4	rotation	80	20	Yes	29.5
F5	Longer	80	50	No	20.8
F6	rotation	80	50	Yes	16.4

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[9] Rice cultivation is a small source of methane in U.S. In 1999, methane emissions from rice cultivation were about 2 percent of total U.S. methane emissions (EPA 2001). However, the amount of methane reduction is substantial on a per acre basis. Based on empirical analysis in subsequent chapters, reduced methane is estimated about 0.76 tons carbon equivalent and it is equivalently 25 percent of total GHG offset in case of afforestation and over 70 percent of the emission offset by a tillage change.

where, *CE*(*t*) is (temporal) carbon sequestration in time *t* and *OE*(*t*) is other permanent GHGE reductions such as removed CH_4, N_2O or CO_2. It is important here that *OE*(*t*) is permanent or is not reversed when producers revert their land management or land use to pre-AO project.

The *NPV* of the benefits from the AO project followed emission in year *ST* in equation (43) changed to:

$$(47)\quad NPV_M^{TM} = \sum_{t=0}^{ST}\left(\int_t^{ST} e^{-rt}P(t)(CE(t)+OE(t))F(t)dt\right)+\int_{ST}^{100} e^{-rt}P(t)OE(t)F(t)dt$$

where, the subscript *M* indicates multiple GHGE offset. Using equation (47), *PERM* is modified as follows:

$$(48)\qquad PERM(\%) = \left(1-\frac{NPV_M^{TM}}{NPV^{PM}}\right)\times 100\,.$$

For illustrational purposes, assume that *CE*(*t*) and *OE*(*t*) are 0.7 tons of CO_2 and 0.3 tons of CO_2 respectively in case of agricultural soil carbon sequestration. In this case, *PERM* decreases relative to the single offset (carbon sequestration) case, because the NPV_{TM}^{M} increases due to permanent GHGE offset, *OE*(*t*). In other words, in year 20, the AO project saturates and is reverted back to intensive tillage or the previous land use then volatility occurs. However, only the sequestered carbon, *CE*(*t*), would be released to the atmosphere, so that the increase in burden to the atmosphere is reduced compared to single offset case. This is illustrated in Figure 10. The area of the curve after *ST* year shows the *NPV* for permanent GHGE offset, *OE*(*t*).

Case A1 is that agricultural producers revert back to conventional tillage or previous crop cultivation after saturation occurs. In this case, *PERM* is calculated as 22.6% while it is 52.2% for the single offset case. Under case A2, the agricultural producers maintain the AO project to save GHG so that *PERM* is again zero (See Table 6).

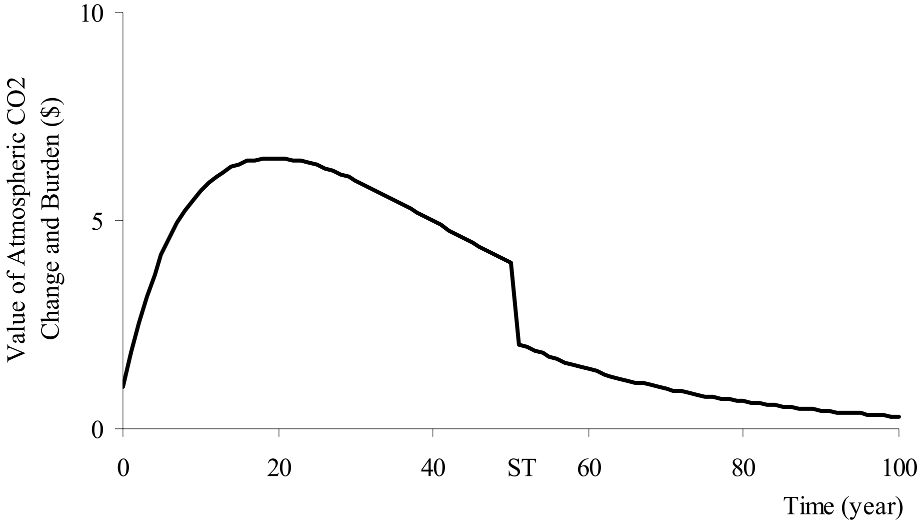

Figure 10. Change in value of atmospheric CO_2 burden under multiple GHGE offset

Table 6. Agricultural Soil Offset and Permanence Discounts under Multi Offset

Cases	Saturation Year	Practice After Saturation	PERM Discount (%)
A1	20	Revert	**22.6**
A2	20	Maintain	**0.0**

Note: we assume that carbon sequestration and permanent GHG offset are 0.7 tons of CO_2 and 0.3 tons of CO_2, respectively.

In the case of afforestation, suppose $CE(t)$ is 0.8 tons while $OE(t)$ is 0.2 tons of CO_2. Cases F1 and F2 are a forest kept to saturation. Under the case F1 with no harvest, *PERM* is zero. Under the case F2 with harvest at year 80 and without reforestation, *PERM* is computed as 3.2% compared with 5.7% for the single offset. Cases F3 and F4 are for shorter rotation with harvests in year 20. Under the case F3 without reforestation after harvest, *PERM* is 32.5% compared with 52.2% for the single offset. Under the case F4 with reforestation, *PERM* is 9.7% while it is 29.5% for the single offset. Cases F5 and F6 are for longer rotation with harvest at year 50. Under the case F5 without reforestation, *PERM* is 11.9% compared with 20.8% for the single offset. Under the case F6 with reforestation, *PERM* is 7.4% while it is 16.4% for the single offset case (See Table 7).

Concluding Remarks

Once an AO project involving soil sequestration is put into place, soil carbon begins to accumulate until it reaches a new equilibrium whereupon the absorptive capacity of the soil is used up and the soil saturates. In the case of crops, the saturation year is around 20 and forestry saturation year is greater than 80.

Table 7. Afforestation and Permanence Discounts Under Multi Offset Case

Cases		Saturation Year	Harvest Age	Reforest after Harvest	Perm Discount (%)
F1	Forest kept	80	Never		**0.0**
F2	to saturation	80	80	No	**3.2**
F3	Shorter	80	20	No	**32.5**
F4	rotation	80	20	Yes	**9.7**
F5	Longer	80	50	No	**11.9**
F7	rotation	80	50	Yes	**7.4**

Note: we assume that carbon sequestration is 0.8 tons of CO_2 and permanent GHG offset is 0.2 tons of CO_2.

Basically, the AO project is no different than other GHGE mitigation options such as direct emission reductions from the GHGE credit buyer's point of a view except that the carbon may not last as long. Thus, as other long-run investment portfolio, the AO project should be compared with other mitigation options and this means that a permanence discount calculation should be made based on the duration over which the carbon is held, the price of carbon and the appropriate interest rate.

In the above material, a formula for computation of permanence discounts is developed and applied. Empirically, example permanence discounts are computed. Most of the case, permanence discounts are found to be positive, which implies that the salable quantities of GHGE offset is less than that of a permanent offset.

When the AO sequestration project also involves permanent GHGE reductions as well as sequestration (multiple GHGE offset), the average permanence discount is reduced, and thus, the salable equivalent GHGE offset increases.

CHAPTER VI

ESTIMATE OF UNCERTAINTY DISCOUNT

Background

There are a variety of uncertainties related to an AO project. Uncertainty here is the term to describe phenomena such as statistical variability, lack of knowledge or surprise with respect to the quantity of GHGE offsets produced (Morgan and Henrion; Hattis and Burmaster, Cullen and Frey; Heath and Smith). Uncertainties can make place decision makers (especially credit buyers) at risk of acquiring an insufficient level of credits. Thus a description of uncertainty may be necessary to provide information for decisions pertaining the AO project. Note that we adopt the simple definition that uncertainty is a lack of confidence in the quantity of GHGE offsets created by an AO program.

The sources of uncertainty in terms of GHGE offsets following (Birdsey and Heath, Heath and Smith) include

- Climate and other factor induced annual production variability in the quantity of GHGE offset produced at a location;
- Aggregation induced sampling error at the regional scale;
- Carbon pool measurement errors; and
- Intertemporal variation in the duration and permanence of carbon sequestered in the future.

Some argue that GHGE offset projects should be paid for delivering the offset level that defines a particular confidence interval not the average amount (Canada). For example, under the environmental trading schemes, there are penalties imposed on shortfall of environmental commitments. Such penalties are imposed within the sulfur dioxide (SO_2) trading implemented in U.S. Generally the penalty for excess emissions of SO_2 is \$2000/ton × annual adjustment factor × tons of excess emissions of SO_2 (Seton's EH&S Compliance Resource Center), which is more than 10 time the observed price.

Shortfall penalties and management actions have been discussed in the context of international GHGE offset arena regarding tradable quantities of emissions. For example, Canada outlined a proposal in which the amount of carbon sequestered by a mitigation measure would be reported along with an estimate of the uncertainty in this measurement and that credits could be claimed only to the extent that there was 90% certainty in the amount sequestered.

An uncertainty discount would be the reduction needed in the (expected) quantity of offsets necessary to reach the desired confidence level. This reduction would be based on the variability in the quantity of GHGE offset (Q). The main questions that need to be answered to form the uncertainty discount is what is the definition over time and space of the quantity that will be discounted, what are the distributional parameters for the Q measure, and then what level of offset could be confidently expected to occur.

Aggregation and Uncertainty

The first item of interest involved with agricultural offsets involves the definition of what is uncertain. Conceptually, the uncertain quantity would be the amount of the carbon accumulated across a geographic region across a multi year agreement. This would be the collection across multiple fields /field segments each of which would exhibit carbon gain variability across multiple years.

The rationale for a normality assumption arises from the Central Limit Theorem[10]. The GHGE credit buyers will likely purchase a large quantity of offsets over a number of years. As a consequence, the GHGE offset quantity will be the sum of contributions from many individual land units over a number of years. Statistically the uncertain quantity is that arising in the sample mean across a geographic and temporal population of offsets produced. The Central Limit Theorem asserts that the distribution of a sample's mean is normally distributed.

We should recognize that aggregation across space and time is expected to reduce the level of uncertainty. Statistically if all farms were alike with a farm level standard deviation of σ and exhibited independent distributions, then the aggregate average amount of carbon would have a standard deviation $\sigma/\sqrt{n}$ by the central limit theorem where n is the number of observations across time and across space (Moore and McCabe). This means if we had a 5 year contract involving 20 farms that the standard deviation of the average increment would be 1/10th the individual standard deviation provided all the assumptions hold.

However, independence assumption may be strong because there exists high correlations in sequestered carbon across space and time. We can use the central limit

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[10] If $\overline{x}$ is the mean of a random sample of size n from a population with mean μ and standard deviation σ, then $\overline{x} \sim (\mu, \sigma / \sqrt{n})$ (Moore and McCabe)

theorem when independence assumption does not hold (as long as the are not too strongly associated) (Moore and McCabe) but we may not use $\sigma/\sqrt{n}$ as a standard deviation. Even if independence is not to be expected, aggregated standard deviation should be the function of sample size and it will decrease when sample size increase. Now we define that aggregated standard deviation is σ_n which is decreasing when sample size increases through aggregation[11].

Derivation of Uncertainty Discount

Calculation of an uncertainty discount is formed based on a confidence interval approach that relies on a statistical distribution of the quantity of GHGE offset, Q. Under the common assumption of a normal distribution we can compute the confidence level and uncertainty discount via standard formulae.

Suppose that GHGE credit buyers are interested in more certain measure of offset volume than the mean. We are only considering the area to the left of the mean because GHGE credit buyers are interested in offset below the mean. For example, assume that GHGE credits will be claimed with 95% certainty. This is illustrated in Figure 11. In Figure 11, Q_C indicates discounted Q, that is the GHGE credit, and $\overline{Q}$ is the mean of Q.

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[11] If iid assumption hold, $\sigma_n = \sigma / \sqrt{n}$

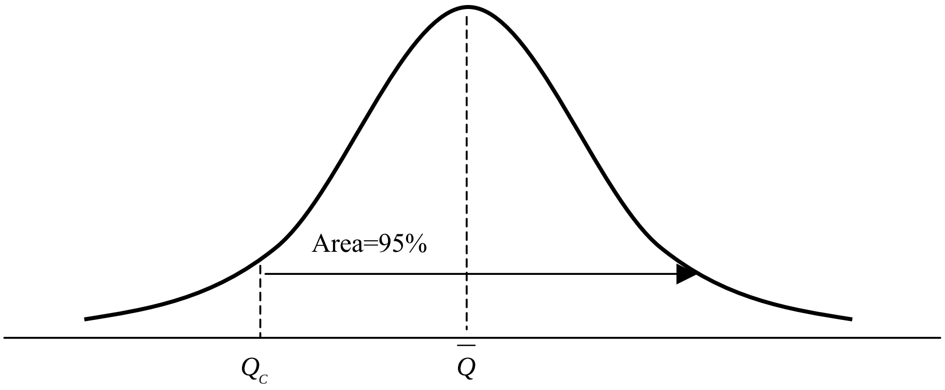

Figure 11. PDF for Q and 95% confidence interval

Suppose we have estimates of the mean and the standard deviation associated with offset rates. Before defining and computing an uncertainty discount, we now define the coefficient of variation (CV) first such that:

$$(49) \qquad CV(\%) = \frac{s_n}{\overline{Q}} \times 100$$

where, $\overline{Q}$ is the mean of Q, s_n is the sample standard deviation of aggregate contract of Q when aggregation level over space and time is n. The CV is a measure of the relative variation of a distribution independent of the units of measurement expressed as a %. It is noteworthy that the CV is affected by sample size, n. The CV decreases when Q is aggregated over space and time as discussed in the above section.

The lower bound of the 95% confidence interval based on the distribution for Q has the following form:

$$(50) \qquad Q_C = \overline{Q} - t^* s_n$$

where, Q_C is discounted Q under 95%, t^* is the critical value for the t distribution with $(n - 1)$ degree of freedom under a 95% confidence level.

Based on equation (50), the uncertainty discount (*UNCER*) is derived as follows[12]:

$$(51) \qquad UNCER(\%) = \frac{\overline{Q} - Q_C}{\overline{Q}} \times 100 = \frac{\overline{Q} - (\overline{Q} - t^* s_n)}{\overline{Q}} \times 100 = t^* \cdot CV .$$

Using equation (50), we can simplify *UNCER* as a function of the confidence interval specification in terms of the percentage safety margin and the CV as shown in equation (51). As discussed above, *UNCER* tends to reduce when Q is formed by the aggregation over space and time due to increases in sample size.

Approximation of Quantity of GHGE Offset Distribution

Unfortunately, the Q distribution may not be easily obtained with reasonable cost due to the lack of data; difficulties in monitoring and sampling. Also measuring sequestration rates for all units of land is impossible since the GHGE offset is sequestered in every square inch of the landscape. In fact, if monitoring and sampling were easy and cheap, there would be no considerations for uncertainty.

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[12] Recall the definition of the GHGE discount in equation (1) such that $\delta(\%) = \frac{Q - Q_C}{Q} \times 100$

This leads to several possibilities including:

(i) Using an biophysical simulation model to develop distribution of Q,

(ii) Using some other items' distribution such as crop yield as a proxy of Q, or,

(iii) Field measurement.

All approaches give us the estimate of the CV for the quantity of GHGE offset, and then we can utilize equation (51).

Biophysical Simulations

In terms of biophysical simulations, the forest carbon budget model FORCARB (Birdsey, Plantinga and Birdsey) makes estimates of carbon quantities and identifies influences on model uncertainty using FORCARB in US forest (Smith and Heath; Heath and Smith). The Erosion Productivity Impact Calculator (EPIC) also simulates estimates of carbon quantities (Izaurralde *et al.*). EPIC was originally developed to assess the impact of cropping practices on crop productivity of various soils (William *et al.*). Recently, EPIC has been expanded to cover the effect of a variety of land use management decisions on soil loss, water quality and crop yield.

Such models can be run over varying weather, soil, and crop management conditions to obtain a distribution of GHGE offset levels. One can also look at the effect of cumulative offset rates over years by running the model for say 25 years and computing the coefficient of variation for 5 year total offset production instead of single year data.

A major problem in this approach arises properly obtaining a coefficient of variation estimate and in properly including the variation canceling aspects of less than perfectly correlated offsets produced across the landscape. Namely, it is reasonable to believe that across individual sites on a farm and across farms in a project there will be a mixture of both unique localized events and correlated weather. For example, hail may be localized but temperature and frontal rains may affect most of a county. On the other hand, such models also ignore a number of factors that are very localized such as wind damage, pest outbreaks, human and wildlife induced damage, soil and topography variations and lightning strikes among many other factors. This implies an underestimation of the coefficient of variation on a plot.

Furthermore, when running with stochastically generated weather it would be difficult to obtain the proper correlation of the weather events across geographic areas and time and would certainly ignore a number of the other less than perfectly correlated more localized events. This implies that one may be able to get estimates of the variance but it would be difficult to properly incorporate spatial correlation. The only potential approach is to use historical weather simultaneously at all plots and correlate the results by year thus incorporating the spatial correlation arising across multiple weather stations.

Crop Yield as Proxy Variable

We might also use crop yield as a proxy variable of the quantity of carbon offset because the carbon input is proportional to plant size, which is proportional to yield (Kimble). An examination of EPIC results shows that the correlations between sequestration rate and crop yields are very high ranging from 0.7 to 0.9 and these are statistically significant. Thus we could assume that the variation in carbon sequestration can be proxied by the variation in crop yield. Crop yield data are widely available from various USDA sources.

However, we cannot use the CV for crop yield as the CV for GHGE offset because error in the estimate of the CV for GHGE offset is unavoidable because there is additional variation in the quantity of GHGE offset. In a regression fitting to Q and crop yield such that $Q_i = a + b^*Y_i + e_i$, where Y is crop yield and e is the associated error term, then the square of the correlation coefficient is the proportion of the total variations in Q which is accounted for by the regression (Weisstein).

Based on regression fitting, we can derive the relationship CVs for crop yield and Q as follows. The squared total variation in Q is $\sum (Q_i - \bar{Q})^2$. From the regression fitting, the squared total variation in Q is expressed as follows:

$$(52)\qquad \sum (Q_i - \bar{Q})^2 = \sum (a + bY_i + e_i - a - b\bar{Y})^2 = b^2 \sum (Y_i - \bar{Y})^2 + \sum e_i^2 \ .$$

From the definition of the coefficient of determination (R^2) (Griffiths, Hill and Judge),

$$(53)\qquad R^2 = 1 - \frac{\sum e_i^2}{\sum (Q_i - \bar{Q})^2}$$

$$\Rightarrow \qquad \sum e_i^2 = (1 - R^2) \sum (Q_i - \bar{Q})^2$$

$$\Rightarrow \qquad \sum e_i^2 = (1 - R^2)[b^2 \sum (Y_i - \bar{Y})^2 + \sum e_i^2]$$

$$\Rightarrow \qquad \sum e_i^2 = \frac{(1 - R^2)}{R^2} b^2 \sum (Y_i - \bar{Y})^2 \ .$$

Substitution equation (53) to equation (52) yields

$$(54)\qquad \sum (Q_i - \bar{Q})^2 = b^2 \sum (Y_i - \bar{Y})^2 + \frac{(1-R^2)}{R^2} b^2 \sum (Y_i - \bar{Y})^2 = \frac{b^2}{R^2} \sum (Y_i - \bar{Y})^2 .$$

From equation (54), we can see the total variation in Q is the proportion of the estimated slope coefficient, b, and R^2 to the total variation in crop yield.

Now, we can get (sample) standard deviations if we divide both sides of equation (54) by $(n - 1)$ and take a square root. That is,

$$(55)\qquad s_Q = \sqrt{\frac{\sum (Q_i - \bar{Q})^2}{n-1}} = \sqrt{\frac{b^2}{R^2} \frac{\sum (Y_i - \bar{Y})^2}{(n-1)}} = \frac{b}{R} s_Y ,$$

where, s_Q is the standard deviation of Q and S_Y is the standard deviation of crop yield. Now, we can derive the relationship between CVs using equation (55). Divide both sides of equation (55) by $\bar{Q}$ and $\bar{Y}$ then we get

$$(56)\qquad \frac{s_Q}{\bar{Q}\bar{Y}} = \frac{b}{R} \frac{s_Y}{\bar{Q}\bar{Y}} \quad \Rightarrow \quad CV_Q = \frac{b}{R} \frac{\bar{Y}}{\bar{Q}} CV_Y$$

$$\Rightarrow \quad CV_Q = \frac{b}{R} \frac{\bar{Y}}{(a + b\bar{Y})} CV_Y$$

$$\Rightarrow \quad CV_Q = \frac{CV_Y}{R} \quad \text{(when } a = 0\text{)}$$

In other words, the CV for GHGE offset is estimated using the CV for crop yield with some adjustment using the slope coefficient and mean.

Field Measurement

The other obvious alternative for estimating the coefficient of variation involves the use of field measurements. Namely, one can measure carbon stock at alternative locations and do other measurements relative to methane, nitrous oxide and carbon dioxide emissions. The difficulty with field measurement is that it cannot really be done before the project is implemented and will not be available until sometime after the project has begun (i.e. to measure the five-year stock one must wait for five years) unless highly similar projects appear within the same region. Clearly such measurements will provide a valuable check on a priori estimates and, if employed, will provide a basis for revising the estimates later during the project life. It may also be difficult to have a large enough sample to accurately estimate the variance reducing properties of the diverse spatial scale of a contract. However, this approach will not be utilized in this study.

Concluding Remarks

The quantity of GHGE offset created by the AO project may need to be adjusted to claim GHGE credits due to regulatory or credit buyers require avoiding the liability of shortfalls. This would invoke an uncertainty discount. In the AO project, the uncertainty discount would reduce credits for offsets from AO, which could be confidently to occur.

To compute the uncertainty discount we need to know the distribution of the GHGE offsets. Unfortunately, it is impossible to observe this distribution in practice. Here, we can use either the environmental simulation model such as EPIC to estimate the distribution or a proxy using the distribution of crop yields. Once we have distributional parameters under the normality assumption, we can compute the uncertainty discount via standard formulae in statistics. It is noteworthy that aggregation over space and time is important.

CHAPTER VII

EMPIRICAL MAGNITUDES OF GHGE OFFSET DISCOUNTS

In this chapter, we examine the empirical magnitudes of GHGE offset discounts for a case study project in the Southeast Texas.

Background

The area in Texas between Beaumont, Houston and Victoria has historically been a rice production area. In 2000, the planted acreage of rice was 214,000 acres, while rice production amounted to 14.3 million cwt and the value of the rice crop was $93 million.

The recent policy and market environment have put pressures on rice acreage and production (USDA, 2001). Rice producers in Texas face high production costs, lack of economically viable rotation crops, low rice prices, diminishing government payments, and weather variability. Considerable reduction in Texas rice production has occurred with a 37% reduction in acreage and a 30% production reduction between 1990 and 2000. Today, many Texas rice producers are in quest of new opportunities.

One possible opportunity for rice farmers would be participation in an AO program. Under a GHGE trading program, rice growers could convert rice fields to other crops, pasture, or forests to reduce net GHGE and be paid by purchasers of GHGE credits such as power plants or governments.

In terms of GHGE, rice is a source of methane emissions caused by anaerobic decomposition of organic matter in a flooded environment. Conversion of rice to less intensively tilled crop-mix, pasture or trees would reduce methane emissions, increase sequestration and probably reduce emissions from nitrogen use, water pumping and farm fuel consumption.

Scenarios

There are several options for an AO project involving rice acreage: conversion of rice fields to (i) other crops, specifically rice to a cotton, sorghum, and soybean crop mix in the region (ii) pasturelands, and (iii) forest uses. We divide each scenario into some sub-scenarios. In cases of (i) rice to other crops, (ii) rice to pasture, there are two sub-cases:

A1 Reverting back to previous management or land use after carbon sequestration saturates (in year 20), and

A2 Continuing the AO practice after saturation based on economic superiority.

In the case of (iii) afforestation, there are three broad options based on forest management and six sub-options based on reforestation.

(F-I) Forests kept to saturation (in year 80),
  F1: No harvest,
  F2: Harvest at year 80 but no reforestation;
(F-II) Shorter rotation (harvest at year 20)
  F3: No reforestation;
  F4: Reforestation;
(F-III) Longer rotation (harvest at year 50)
  F5: No reforestation
  F6: Reforestation.

Quantity of GHGE Offset

The quantity of GHGE offset (*Q*) from a rice land conversion consists of four parts, (i) sequestered carbon in soil and trees, (ii) saved GHG from discontinuing rice cultivation, (iii) reduction in fossil fuel usage for machinery, and (iv) change in emissions stimulated by nitrogen fertilizer and irrigation use.

Sequestered Carbon

Estimates of changes in sequestered carbon are obtained through use of the Erosion Productivity Impact Calculator (EPIC). EPIC was originally developed to assess the impact of cropping practices on crop productivity of various soils (Williams *et al*.). Recently, EPIC has been expanded to cover the effect of a variety of land-use management decisions on soil loss, water quality and crop yield.

In addition EPIC now estimates carbon sequestration (Izaurralde *et al*.). For more details about EPIC model, refer to Izaurralde *et al*., and http://www.brc.tamus.edu/ epic/ introduction/aboutepicmodel.html. In this study, the rate of carbon sequestration is calculated based on the simulated carbon pool results developed by EPIC:

$$(57) \qquad \text{Rate of SOC/ac/yr} = \frac{\text{Final SOC/ac} - \text{Initial SOC/ac}}{\text{Number of Simulated Years}}.$$

That is, the periodic average annual rate of SOC is the difference between two estimates of SOC divided by the length (in years) as shown in equation (57) (Smith and Heath).

In case of afforestation in rice fields in Southeast Texas area, the annual rate of SOC is estimated from EPIC as 3.0 tons/ac/yr. In case of conversion to crop mix[13], the annual rate of SOC is 0.4 tons/ac/yr and the annual rate of pasture SOC is 1.7 tons/ac/yr. These numbers can be compared with other science researches on rate of SOC for forest and pasture establishment after agricultural use.

Post and Kwon review literatures that reports rate of SOC after changes in land-use that favor carbon accumulation. The average of rate of SOC for afforestation is 3.2 tons/acre and the average of rate of SOC for pasture is 2.0 tons/acre in warm temperature zone even if there is a large amount of variation in rates (refer to Post and Kwon for more details).

Saved GHG

Methane

All of the rice in Texas is grown under flooded conditions. When fields are flooded, aerobic decomposition of organic material gradually depletes the oxygen present in the soil and floodwater, and anaerobic conditions develop in the soils. At that point, methane is produced through anaerobic decomposition of soil organic matter by methanogenic bacteria. As much as 20 to 40 percent of the methane produced is transported from the soil to the atmosphere primarily by diffusive transport through rice

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[13] A crop mix is the percentage of planted acres for each crop in the specific region relative to the total planted acres in the region. This method establishes the typical cropping practice in a county and weights each crop according to its importance. Based on historical data, crop mix for the Southeast Texas is composed of sorghum, soybean and cotton.

plants (Holzapfel-Pschorn *et al*.; Sass *et al*.; US EPA 1999). When rice cultivation is discontinued, methane emissions are removed.

Methane emissions from rice cultivation can be estimated using the method suggested by US EPA that involves the acreage of rice grown in an area, estimates of the average number of days flooded, and emission factors for the amount of methane emitted per acre-day of flooding (US EPA 1999). It is noteworthy that we should convert the methane emission to metric tons of carbon equivalent for comparison using global warming potential.

Once we get the methane emission in metric tons then we multiply by 12/44 (the ratio of the molecular weight of carbon to the molecular weight of CO_2) and by 21 (the 100-year global warming potential of methane as in IPCC report, US EPA, 2001) to obtain methane emissions in metric tons of carbon equivalent. Under this calculation, average annual methane emissions are 0.76 tons/ac/yr of carbon equivalent.

Reduced Carbon from Reduction in Fuel Usage

When producers use machinery for cultivating and irrigating rice fields, they use fossil fuels and emit carbon dioxide. Carbon dioxide emission is calculated using formulas developed by US EPA (2003) (http://www.epa.gov/region4/air/cai/formulas_main.htm).

According to US EPA (2003), 1 gallon of fuel emits 22 lbs carbon dioxide. Based on the budget table for rice cultivation, average usage of fossil fuel is approximately 11.2 gallons/ac/yr (Anderson). The carbon dioxide emission associated with this works out to be 246.4 lbs/ac/yr and in turn it is 0.03 tons/ac/yr of carbon equivalent. Note that we assume to be no reductions in fuel usage in case of conversion to crop mix.

Table 8. Total Quantity GHGE Offset Under Each Alternative (Unit: ton/ac/yr of carbon equivalent)

	Rice to Crop Mix	Rice to Pasture	Rice to Forests
Sequestered Carbon	0.40	1.69	3.02
Methane	0.76	0.76	0.76
Saved Fuel Usage	0.00	0.03	0.03
Total	1.16	2.50	3.81

Total Quantity of GHGE Offset

Based on the above results, total quantity of GHGE offset per acre under each alternative is calculated. Table 8 contains all the results. Afforestation offsets rate is the largest which is estimated as 3.81 tons/ac/yr of carbon equivalent and pasturelands saves GHGE of 2.50 tons/ac/yr of carbon equivalent while a conversion to crop mix yields 1.16 tons/ac/yr of carbon equivalent. In other words, we can expect to save 3.81 tons/ac/yr of carbon equivalent when we convert rice field to forests lands.

Additionality

As discussed in Chapter III, the GHGE offset based on the AO project should be additional to the baseline that is change expected by extrapolation of historical trends. In an AO project, the additionality is concerned when the region where a project is being proposed has had substantial adoption of the AO practice in the absence of GHG programs, and this adoption is expected to continue. In such a case, a discount for the region may need to reflect business-as-usual AO practices adoption. In the Southeast Texas case study, we need to examine the without project incidence of rice land conversion to other uses.

We will use the project-based approach to determine the additionality discount in Chapter III. For doing this, we need the estimates of land use transitions and will then compute baseline GHGE offset. In order to estimate the land use transitions, we will utilize the Markov transition matrix and the econometric so-called land share model. After finding land conversion rates, we will estimate the additionality discount.

Under the project-based approach, we will determine the baseline using historical data in the project area and estimate of expected GHGE offset created by the land use changes. However, errors in the estimate of the additionality discount are unavoidable because precise baseline estimation is impossible.

Estimation of Land Conversion Rates

Land Conversion Rates with Markov Matrices

Table 9 contains a Markov land transition matrix for the Southeast Texas area for 1992-1997 drawn from the Census of Agriculture for 1992 and 1997. Note that reading across the row, we find the probabilities that were converted to another use between observations.

The Markov land transition matrix in Table 9 is 5-year transition probabilities so that we need to develop one-year transition probability matrix. Since n-year transition probability matrix can be obtained by computing the nth power of the one-year transition probability matrix (Hiller and Lieberman), we can find one-year transition probability matrix using the nth roots of n-year transition probability matrix. This can be done using a GAMS program, which finds the fifth roots of Markov transition matrices by minimizing the deviations between the fifth power of a matrix and the observed 5-year transition. In turn, estimates of the annual conversion rates are obtained (See Table 10).

Land Conversion Rates with Land Share Model

For the econometric model of land use, equation (23) in Chapter III is estimated using data on land use. Each cropland, forest, and urban land share, denoted $y_k(t, j)$, is defined as the share of total land in each county. County-level observations are available from the Census of Agriculture for 1992 and 1997, Forest Inventory and Analysis Data Bases Retrieval System (http://www.srsfia.usfs.msstate.edu), and the Texas Almanac (Ramos).

Table 9. Markov Transition Matrix for Southeast Texas for 92-97 (Probability)

To From	Corn	Sorghum	Wheat	Rice	Cotton	Soybean	Hay	Others[1]	Woodland	Other[2]	Pasture	1992 total
Corn	**0.742**	0.047			0.014	0.068	0.051	0.016		0.062		1.00
Sorghum		**1.000**										1.00
Wheat		0.023	**0.872**		0.007	0.034	0.025	0.008		0.031		1.00
Rice		0.048		**0.736**	0.014	0.070	0.052	0.016		0.063		1.00
Cotton					**1.000**							1.00
Soybean						**1.000**						1.00
Hay							**1.000**					1.00
Others								**1.000**				1.00
Woodland		0.029				0.042	0.032	0.010	**0.839**	0.039		1.00
Other										**1.000**		1.00
Pasture											**0.998**	1.00
1997 total	0.742	1.147	0.872	0.736	1.035	2.249	1.160	1.050	0.839	1.195	0.998	

Source: Census of Agriculture 1992 and 1997

Note: [1] Other crops and [2] Land in house lots, ponds, roads, wasteland, etc

Table 10. Annual Rate of Conversion from Markov Matrix (unit: %/yr)

Cases	Rice to								
	Rice	Sorghum	Cotton	Soybean	Hay	Other[1)]	Others[2)]	Pasture	Wood
Conversion Rates	94.7	0.96	0.28	1.4	1.04	1.26	0.32	0.00	0.00

Note that conversion rates of other land uses not listed are zero
1) Other implies other crops
2) Others implies land in house lots, ponds, roads, wasteland, etc

As suggested in Chapter III, a land share equation involves a function of net returns from specific land use, and land quality. Net returns denoted $NR_k(t, j)$ are defined as the present discounted value for an infinite stream for timber and as the net return in time *t* for crops. Land Capability Class (LCC) rating, denoted *L*(*j*) can be used as proxies for land quality variable. LCC ratings are derived from county-level soil surveys and based on twelve soil characteristics such as slope, permeability etc. Note that *L*(*j*) is not indexed by *t* because land quality measures remain constant over time. Also, population density is used as one of the explanatory variables. In other empirical land use analyses, population measures are used to account for the allocation of land to non-rural uses. Specifically, the following equations are estimated:

$$
\begin{aligned}
\ln(y_k(t,j)/y_{RICE}(t,j)) = {} & \beta_{k0} + \beta_{k1} NR_{RICE}(t,j) + \beta_{k2} NR_{SORG}(t,j) + \\
& \beta_{k3} NR_{COTT}(t,j) + \beta_{k4} NR_{CORN}(t,j) + \\
& \beta_{k5} NR_{SOYB}(t,j) + \beta_{k6} NR(t,j) + \\
& \beta_{k7} NR_{TREE}(t,j) + \beta_{k8} PD(t,j) + \beta_{k9} L(j) + e_k(t,j)
\end{aligned}
\tag{58}
$$

where, *PD*(*t*, *j*) is population density and $e_k(t,j) \sim (0, \Omega_k)$ and Ω_k are assumed to be diagonal matrices.

Equation (58) can be estimated with ordinary least squares. The procedure from White is used to correct the estimates for an unknown form of heteroscedasticity, and the procedure in Newey and West autocorrelation-consistent matrix with order 1 is used to correct an autocorrelation problem in the model.

Net returns for each crop equal the real annual per-acre net revenues, which are revenue (price times yield) less variable production costs[14]. Price, yield and cost data are obtained from Texas Agricultural Statistics Service for each year and Texas Crop Enterprise Budgets from Texas Agricultural Extension at Texas A&M University System (Anderson)[15]. Net return for forest is measured as the annuity equivalent of the 20 years (F4; short rotation, multiple harvest case) stream of timber revenues per acre base. Timber production data are from, FASOM, Xu and Forestry Inventory and Analysis databases retrieval system (http://www.srsfia.usfs.msstate.edu). Forest production costs data are from Dubois, Erwin and Straka.

Total differentiation of equation (58) indicates that the estimated coefficients measure the percentage change in the share ratios for one-unit change in the independent variables. In other words, *ceteris paribus*, a one-unit change in the rice rent increases or decreases the ratio of other crop or forestland by estimated coefficients.

Estimation results are reported in the Table 11. The variable *Sorg/Rice* indicates the ratio of sorghum acreage to rice acreage as a dependent variable, and others have

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[14] 5 year average prices are used when crop revenues are calculated since Census of Agriculture is surveyed for 5- year term. In other words, the data in 1992 or 1997 are assumed to reflect past 5-year producers' behavior

[15] Costs are assumed to be constant over the region (county).

analogous definition. The variable *N_Rice* indicates net return of rice, and other variables have definitions. The variable *PD* indicates the population density and *L* indicates the soil quality. All of coefficients for net return of rice are significantly negative. It implies that increasing net return of rice reduces other crops' acreage. From the Table 11 (especially, the coefficient of net returns for rice), conversion rates can be obtained (See Table 12).

Table 11. Land Share Model Estimation Results

Variables	Sorghum/Rice	Cotton/Rice	Corn/Rice	Soybean/Rice	Pasture/Rice	Tree/Rice	Urban/Rice
N_Rice	-0.0257*	-0.0193*	-0.1526	-0.0303*	-0.0242*	-0.0191*	-0.0236*
(Net return of rice)	(-4.507)	(-3.460)	(-1.877)	(-8.664)	(-7.646)	(-8.336)	(-5.514)
N_Sorg	0.0056	0.0099	-0.0269**	0.0076	-0.0088	-0.0123*	-0.0039
(Net return of sorghum)	(0.568)	(1.033)	(-2.218)	(0.892)	(-1.827)	(-2.440)	(-0.407)
N_Cott	-0.0079*	-0.0081*	0.0006	-0.0054*	-0.0038*	-0.0044*	-0.0036
(Net return of cotton)	(-3.152)	(-3.009)	(0.167)	(-3.172)	(-2.610)	(-2.784)	(-1.174)
N_Corn	0.0051	0.0032	0.0191*	0.0070	0.0188*	0.0204*	0.0243*
(Net return of corn)	(0.787)	(0.452)	(2.557)	(1.166)	(8.027)	(8.717)	(5.756)
N_Soyb	0.0063	-0.0018	-0.0055	0.0115	0.0151**	0.0130*	0.0256**
(Net return of soybean)	(0.509)	(-0.126)	(-0.299)	(1.849)	(2.369)	(2.619)	(2.160)
N_Past	0.0104**	0.0050	0.0015	0.0132**	0.0213*	0.0266*	0.0213*
(Net return of pasture)	(2.094)	(1.062)	(0.196)	(2.236)	(10.80)	(10.98)	(6.933)
N_Tree	0.2812*	0.2986*	0.0463	0.0688	0.1660*	0.1371*	0.1932*
(Net return of tree)	(2.533)	(2.484)	(0.406)	(0.904)	(3.674)	(3.127)	(2.728)
PD	1.3041	2.7394*	-2.0270	2.0859*	1.7666*	1.8899*	3.1479*
(Population density)	(1.328)	(2.656)	(-1.866)	(2.965)	(3.227)	(2.794)	(3.192)
L	-0.0214	-3.1301*	-2.4137	1.8719	2.0357*	5.9165*	1.5310
(Soil quality)	(-0.018)	(-2.483)	(-1.338)	(1.148)	(3.457)	(6.477)	(1.410)
Constant	-9.3473**	-8.6612	1.0078	-4.4419	-5.2724*	-9.7507*	-8.0164*
	(-1.957)	(-1.729)	(0.1925)	(-1.093)	(-3.307)	(-5.579)	(-2.824)
R-square	0.7579	0.7834	0.6443	0.8411	0.8845	0.8778	0.7790
Durbin-Watson	2.1567	2.2971	2.6467	2.1082	2.8372	2.0670	2.4782
Log Likelihood	-14.7226	-15.3944	-20.7512	-12.9992	-5.7455	-5.8854	-14.9731

Note: T-values are in parentheses, * denotes significance at the 5%, and ** at the 10% level.
Sample size is 32 for each equation (Full sample size is 224).
Variable descriptions are in parentheses below each variable.

Table 12. Conversion Rates in SE Texas from Land Share Model

	Sorg/Rice	Cott/Rice	Corn/Rice	Soyb/Rice	Past/Rice	Fore/Rice
Ratio Increase by (%)	0.9472	0.6684	0.4775	1.0723	1.1244	0.9439
1997 Ratio	1.0893	0.6729	0.5161	0.5174	12.0941	1.5384
Increase to	1.0997	0.6774	0.5186	0.5230	12.2300	1.5529
Conversion (acres)	1321.2	720.9	436.2	979.4	2763.2	1529.1
Conversion Rate (%)	0.4914	0.2681	0.1623	0.3643	1.0278	0.5688

Estimation of Additionality Discount

Several assumptions are needed to find the additionality discount. Assume that the program horizon is 100 years and the year of saturation is assumed to be 20 for sequestration on cropland and the year of saturation is 80 for afforestation. Note that the proposed AO programs are (i) rice to other crops, (ii) rice to pasture and (iii) rice to forest.

Additionality in Rice to Other Crops

In case of rice to other crops, we assume that producers rotate sorghum, soybean and cotton on rice fields. The approximation of rotation ratio of sorghum, soybean and cotton historically is 2:1:2 during 1990-2000. In turn, the additionality discount (*ADD*) for crop mix can be computed as follows:

$$(59) \qquad ADD_{MIX} = \frac{\sum_{t=0}^{20} B_{t,SORG} + \sum_{t=0}^{20} B_{t,COTT} + \sum_{t=0}^{20} B_{t,SOYB} + \sum_{t=0}^{20} B_{t,HAY}}{0.4 \times \left(\sum_{t=0}^{20} A \cdot SR_{t,SORG} + \sum_{t=0}^{20} A \cdot SR_{t,COTT} \right) + 0.2 \times \sum_{t=0}^{20} A \cdot SR_{t,SOYB}} \times 100$$

where, *B*(*t*) is the total amount of baseline GHGE reductions in time *t*, *A* is the total project area, $SR_k(t)$ is net AO offset rate for alternative *k* in time *t*. $SR_k(t)$ can be obtained from EPIC model as discussed in the above section.

From equation (59), *ADD* for conversion to other crops is found to be (i) 30.7% with the Markov model, and (ii) 23.8% with the land share model. Thus, *ADD* estimate for crop mix is presumed to be 27.3% that is an average of both. It implies that the GHGE credit created by a conversion to other crops is 72.3% of credits or 72.3 units when producers offset 100 units of GHGE.

Additionality in Rice to Pasture

Using the same method, we can find additionality in rice to pasture program. *ADD* for pasture will be as follows:

$$(60) \qquad ADD_{PAST} = \frac{\sum_{t=0}^{20} B_{t,SORG} + \sum_{t=0}^{20} B_{t,COTT} + \sum_{t=0}^{20} B_{t,SOYB} + \sum_{t=0}^{20} B_{t,HAY}}{\sum_{t=0}^{20} A \cdot SR_{t,PAST}}$$

Note that there is no conversion of rice lands to pastureland observed in the Southeast Texas during 1992-1997 so that we may conclude that there is no additionality discount in case of converting to pasturelands. However, *ADD* would not be zero because the land would have been converted to other land uses as illustrated in Chapter III.

From equation (60), *ADD* for pasture is found to be (i) 15.0% with the Markov model, and (ii) 11.7% with the land share model. We use an average of both *ADD* estimates as the *ADD* for pasture option, which is 13.4%.

Additionality in Rice to Forest (Afforestation)

Using the same procedure, we can find additionality in rice to forest program. *ADD* for afforestation will be as follows:

$$(61) \qquad ADD_{TREE} = \frac{\sum_{t=0}^{20} B_{t,SORG} + \sum_{t=0}^{20} B_{t,COTT} + \sum_{t=0}^{20} B_{t,SOYB} + \sum_{t=0}^{20} B_{t,HAY}}{\sum_{t=0}^{80} A \cdot SR_{t,TREE}}$$

Note that there is no conversion of rice field to forestland in the Southeast Texas during 1992-1997 so that we might conclude that there is no additionality discount in case of afforestation. But this would be wrong, as rice lands would have been converted to other uses as we pointed out above. From equation (61), *ADD* for afforestation is found to be (i) 3.1% with Markov model, and (ii) 2.4% with land share model. *ADD* estimate for afforestation is presumed to be an average, 2.8%.

Additionality Discount and Implications

Table 13 summarizes above results. As shown in Table 13, all the additionality discounts are positive. Note that positive additionality discount reduces the salable GHGE offset. It is noteworthy that the additionality discount for conversion to afforestation seems to be zero in the Southeast Texas because there is no conversion to forestlands from rice fields observed during 1992-1997. However, when considering the baseline trend of rice to convert to other uses, the additionality discount is 2.8%.

Table 13. Additionality Discounts in Southeast Texas (Unit: %)

Cases	From Markov Model	From Land Share Model	Average ADD
Rice to Crop Mix	30.7	23.8	**27.3**
Rice to Pasture	15.0	11.7	**13.4**
Rice to Forest	3.1	2.4	**2.8**

It shows that consideration of multiple land uses is important. That is, 2.8% of the projected GHGE offset would occurs in the case due to land use change but none of that would involve afforestation. Also, an AO project which has a high carbon sequestration rate has a small *ADD* such as pasture and forests as shown in Table 13 because the business-as-usual offset consequences are much smaller than the project offsets.

Leakage

As discussed in Chapter IV, the quantity of GHGE offset can be reduced by an induced increase in economic activity and consequent GHGE in other areas when the AO project goes into effect. This implies that the quantity of GHGE offset by the AO practice should be adjusted by a leakage discount.

When the AO policy causes a switch from rice fields into pastureland or forestland, rice production falls so that total rice supply will decrease. But hay or timber production may increase. This causes rice prices to rise and hay or timber prices to decrease when the *ceteris paribus* assumption holds. This change in prices stimulates producers who are not in the AO program to increase their land allocation to rice and reduce pasturelands or forest assuming no management change and equal GHGE rates, when lands are reallocated, leakage can occur.

Leakage Estimation

Recall the leakage discount formula in Chapter IV is:

$$(62) \qquad LEAK(\%) = \left(\sum_{k=1}^{K} \frac{E_S \phi L_{Out}^0}{E_S - E_D(1 + E_{Input}\phi)} \frac{CR_{kOut}}{CR_{Out}} \cdot SR_{kOut} \right) \frac{1}{L_{Proj}^0 \cdot SR_{Proj}} \times 100$$

where, k depicts each source such as other croplands, pastureland or forests lands, SR_{kOut} is the sequestration rate of alternative k, CR_{kOut} is the (absolute value of) conversion rate from or to the k alternative and CR_{Out} is the total conversion rate that is defined as $CR_{Out} = \sum CR_{kOut}$ and SR the net emission rate. Also, E_S indicates the supply elasticity, E_D is the demand elasticity and E_{Input} is the input (land) elasticity. Finally, L_{Proj}^0 indicates the initial land allocation in project area.

Necessary parameters are estimated based on NASS/USDA crop and price data available at http://www.ers.usda.gov/data/psd. Total U.S. rice acreage is 3.04 million acres in 2000, and outside of the Southeast Texas rice acreage is 2.83 million acres. Total rice production is 190.87 million cwt and outside of the Southeast Texas rice production is 176.53 million cwt.

The input (land) elasticity, E_{Input}, which is defined in equation (32) in Chapter IV, is obtained using a simple regression with supply on harvested acreage from 1981 – 1999 including a trend variable. We assume that the input elasticity is constant over time and regions. We use least squares with a Cochrane-Orcutt procedure to correct for serial correlation. Results are as follows (Numbers in parentheses are p-values):

$$\begin{array}{l}\text{Ln } Q^S = \underset{(0.0048)}{-2.7054} + \underset{(0.0000)}{0.9003}\text{ Ln } L - \underset{(0.0146)}{0.0099}\,Trend\end{array}$$

R-Square = 0.924 DW = 1.92

where, Q^S is rice supply and L is harvested acreage. From the above results, the input elasticity of the land is estimated as 0.9003. In other words, rice supply increases by 0.9% when rice land increases by 1% or vice-versa.

The rice demand elasticity, E_D, is found again using a simple regression where we regress total rice consumption on rice price, rice expenditure and CPI. We assume that the demand elasticity is constant. We use least squares with a Cochrane-Orcutt procedure to correct for serial correlation to estimate the rice demand elasticity. Also we impose a homogeneity restriction on the equation. Results are as follows (Numbers in parentheses are p-values):

$$\text{Ln } Q^D = \underset{(0.0006)}{0.9064} - \underset{(0.0000)}{0.9139}\text{ Ln } P - \underset{(0.0002)}{0.1672}\text{ Ln } CPI + \underset{(0.0000)}{1.0811}\text{ Ln } Expenditure$$

R-Square = 0.924 DW = 2.00

where, Q^D is rice use, P is rice price, CPI is consumer price index which is a proxy of prices of substitute and complementary goods and *Expenditure* is expenditures for rice. From above results, the demand elasticity is estimated as –0.9139.

Rice supply elasticity, E_S, can be also found using a simple regression of rice production on price. We assume that the supply elasticity is constant. We use least squares with the Cochrane-Orcutt procedure to correct for serial correlation to estimate the following equation. Results are as follows (Numbers in parentheses are p-values):

$$\begin{array}{l} \text{Ln } Q^S = \underset{(0.0801)}{8.0517} + \underset{(0.0165)}{0.3760} \text{ Ln } P - \underset{(0.8377)}{0.1884} \text{ Ln } PPF + \underset{(0.5207)}{0.0117}\, Trend \end{array}$$

$$\text{R-Square} = 0.510 \qquad \text{DW} = 1.80$$

where, Q^S is rice supply, P is rice price, PPF is price paid by farmer which is a proxy variable for input prices. From above results, the supply elasticity is estimated as 0.3760.

For calculating leakage, we need to look at where land goes and comes from. As discussed in Chapter IV, leakage may occur through more than one market. In other words, land use change in outside of project area can be further segmented into some parts for considering land conversion involving different markets such as products from croplands, pasture or forestry. To do this, there is need to predict land use change and it can be done with a Markov model. We develop the Markov transition matrix for outside of the Southeast Texas (See Table 14). This shows that rice land has been converted to corn, soybean, forestlands and other such as lands in house, roads or wasteland in the rest of the U.S.

Table 14. Markov Transition Matrix for Outside of Southeast Texas (Probability)

To From	Corn	Sorghum	Wheat	Rice	Cotton	Soybean	Hay	Others1)	Woodland	Other2)	Pasture	1992 total
Corn	**1.000**											1.000
Sorghum	0.055	**0.447**		0.003	0.017	0.230	0.070		0.050	0.127	0.001	1.000
Wheat	0.007		**0.875**	0.001	0.007	0.054	0.019		0.009	0.027		1.000
Rice	0.002			**0.984**		0.005			0.004	0.004		1.000
Cotton	0.019				**0.883**	0.034	0.003		0.028	0.032		1.000
Soybean						**1.000**						1.000
Hay							**1.000**					1.000
Others	0.010				0.001	0.031	0.007	**0.920**	0.013	0.018		1.000
Woodland	0.001					0.001			**0.997**	0.002		1.000
Other										**1.000**		1.000
Pasture	0.005		0.005	0.004	0.001	0.005	0.008	0.013	0.002	0.011	**0.947**	1.000

Source: Computed from Census of Agriculture, 1992 and 1997

1) Other crops

2) Land in house lots, ponds, roads, wasteland, etc

The Markov land transition matrix in Table 14 is a 5-year transition probabilities so that we need to develop one-year transition probability matrix. Since n-year transition probability matrix can be obtained by computing the nth power of the one-year transition probability matrix (Hiller and Lieberman), we can find one-year transition probability matrix using the nth roots of n-year transition probability matrix again using GAMS.

Once we find one-year transition probabilities, then the annual land use conversion rate is obtained (See Table 15). Note that carbon sequestration rates are simulated for each case using the EPIC crop simulator. And these are assumed to be the same outside of Southeast Texas as in.

In this case, equation (62) can be rewritten as follows:

Table 15. Conversion Rate and Sequestration Rate for Outside of Southeast Texas

Cases	Conversion Rate (CR_k)	Weights (CR_k/CR)	Sequestration Rate (SR_k)
Rice to Corn	0.04 %/year	0.133	-0.04 ton/acre
Rice to Soybean	0.10 %/year	0.333	1.75 ton/acre
Rice to Forest	0.08 %/year	0.267	3.05 ton/acre
Rice to Other	0.08 %/year	0.267	0.89 ton/acre
Sum	**0.3 %/year (CR)**	**1.000**	

$$\begin{aligned} LEAK(\%) = {} & \frac{E_S \varphi L_U^0}{E_S - E_D(1 + E_{Input}\varphi)} \times \\ & \left(\frac{CR_{corn} SR_{corn}}{CR} + \frac{CR_{soyb} SR_{soyb}}{CR} + \frac{CR_{hay} SR_{hay}}{CR} \right. \\ & \left. + \frac{CR_{tree} SR_{tree}}{CR} + \frac{CR_{other} SR_{other}}{CR} \right) \times \frac{1}{L_R^0 \cdot SR_{AO}} \times 100 \end{aligned} \tag{63}$$

where, each subscript indicates each crop or alternative. The other subscripts indicate lands in house lots, ponds, roads, wastelands, etc. Note that subscript AO stands for crop mix, pasture and tree. Based on the above results, a leakage discount for each AO project is calculated using equation (63). Table 16 contains the results.

Table 16. Leakage Discount for Each AO Project (Unit:%)

Alternatives	Crop Mix	Pasture	Afforestation
LEAK	**38.5**	**17.9**	**11.7**

Leakage Discounts and Implications

We compute that the leakage discount for the conversion rice to other crops in Southeast Texas area as 38.5%. This implies that if there are 100 units of GHGE offsets in the Southeast Texas area through this project, there are additional GHGE of 38.5 units stimulated outside of the Southeast Texas, and in turn, the salable GHGE offset is only 64.6 units. Also, rice to pasture projects leak at a rate of 17.9% and rice to afforestation leaks at a rate of 11.7%.

Permanence

As discussed in Chapter V, an AO project is not necessarily permanent. Namely, once the AO project is put into place, the realized soil carbon gains are stored in a volatile form and the annual rate of carbon gains are not the same over time. In particular, the soil carbon content reaches a new equilibrium when the soil saturates. Furthermore, when the AO practice is discontinued, most of the carbon is released quickly to the atmosphere. In this context, we need additional considerations since these permanence characteristics change the GHGE credits generated by the AO project.

Table 17. Proportion of Sequestered Carbon and Other Permanent Emission Offset

		Crop Mix	Pasture	Afforestation
Sequestered Carbon	(CE)	0.310	0.681	0.793
Other (permanent)	(OE)	0.690	0.319	0.207

Note: All numbers are proportion to total GHGE offsets

As argued in Chapter V, to compute the permanence discount, we need assumptions for carbon price, time horizon (equivalence time, *Te*), and interest rate. We assume that carbon price, *P*(*t*) is $1/ton and constant over time, the time horizon is 100 years, and interest rate is 4% per year. Note that we consider multiple offset cases in this analysis so that we need to decompose the quantity of GHGE offset into temporal offset (*CE*) and permanent offset (*OE*), which is reported in Table 17. Recall the permanence discount equation,

$$(64) \qquad PERM(\%) = \left(1 - \frac{NPV^{TM}}{NPV^{PM}}\right) \times 100 = \left(1 - \frac{\sum_{t=0}^{ST} \int_{t}^{ST} e^{-rt} P(t) Q(t) F(t) dt}{\sum_{t=0}^{ST} \int_{t}^{100} e^{-rt} P(t) Q(t) F(t) dt}\right) \times 100 .$$

where, *ST* is saturation year, *P*(*t*) is carbon price in time *t*, and *Q*(*t*) is the quantity of GHGE offset in time *t*.

Table 18. Permanence Discounts for Rice to Other Crops

Cases		Saturation Year	Practice After Saturation	**PERM (%)**
Rice to	A1	20	Revert	**3.7**
Crop Mix	A2	20	Maintain	**0.0**
Rice to	A1	20	Revert	**29.7**
Pasture	A2	20	Maintain	**0.0**

Permanence Discount in Rice to Other Crops and Pasture

Based on Table 17 and equation (64), we can calculate permanence discounts. Table 18 contains permanence discounts for crop-mix and pasture alternatives. Positive permanence discounts reduces the salable GHGE offset. Case A1 for crop mix exhibits the positive permanence discounts of 3.7% and Case A1 for pasture exhibits 29.7%. Cases A2 for crop mix and pasture has a zero permanence discount because there is no volatility after saturation as discussed in Chapter VI. Note that case A1 for crop mix exhibits a small *PERM* because the permanent GHGE offset is relatively large to temporal carbon sequestration (see Table 17).

Permanence Discounts in Afforestation

In the case of afforestation, volatility occurs when lands revert to agricultural use after harvest or much of above and belowground carbon is removed in the harvesting process. The afforestation case, the calculation of permanence discount is more complicated than agricultural soil offset because there is need to include (i) timing of forest harvest (rotation type: shorter rotation or longer rotation), and (ii) whether reforestation occurs after harvest.

When reforestation is not allowed, we can utilize equation (64) directly to estimate permanence discount. However, we need to modify equation (64) when we consider reforestation to reflect re-accumulation of carbon. Recall the permanence discount formula when reforestation is allowed:

$$(65) \qquad PERM(\%) = \left(1 - \frac{NPV_R^{TM}}{NPV^{PM}}\right) \times 100 = \left(1 - \frac{\sum_{n=1}^{N}\left(\sum_{t=0}^{RY_n}\int_t^{RY_n} e^{-rt}P(t)Q(t)F(t)dt\right)}{\sum_{t=0}^{ST}\int_t^{100} e^{-rt}P(t)Q(t)F(t)dt}\right) \times 100$$

where *RYn* is nth rotation or harvest year.

Based on Table 17 for the multi-offset case and equation (64), we can calculate permanence discounts. Table 19 contains permanence discounts for afforestation. Most of the permanence discounts are positive which imply that the salable GHGE offset reduced by permanence. Shorter rotations (F3 and F4) exhibit the large permanence discounts.

Table 19. Permanence Discounts for Afforestation

Cases		Saturation Year	Harvest Age	Reforest after Harvest	**PERM** (%)
F1	Forest kept	80	Never	-	**0.0**
F2	to saturation	80	80	No	**3.1**
F3	Shorter	80	20	No	**31.9**
F4	rotation	80	20	Yes	**9.2**
F5	Longer	80	50	No	**11.6**
F6	rotation	80	50	Yes	**7.1**

Uncertainty

As discussed in Chapter VI, the term uncertainty is used to describe variations in the quantity of GHGE offsets produced due to climatic/environmental variability, lack of knowledge or surprise. We adopt the simple definition that uncertainty is a lack of confidence in a GHGE offset.

Conceptually the uncertain quantity would be the quantity of GHGE offset accumulated across a geographic region and across a multi year agreement. This would be the collection across multiple fields /field segments each of which would exhibit yield variability across multiple years. For the purposes of this study, we will assume this can be proxied by the agricultural district (which is a combination of several counties) level GHGE offset distribution on a multi year basis (we will use 5 years).

Recall an uncertainty discount (*UNCER*) under given confidence interval based on the normality assumption:

$$(66) \qquad UNCER(\%) = t^{*} \cdot CV$$

where, the CV is the coefficient of variation of the GHGE offset in the region and t^{*} is the critical value for the *t* distribution with (n – 1) degree of freedom under a given confidence level. As argued in Chapter VI, it is difficult to estimate the CV of the GHGE offset because it is impossible to find distributional parameters to define the GHGE offset density function with a reasonable cost due to the lack of data coupled with difficulties in monitoring and sampling.

In this study, we propose two approaches: (i) Use the CV of crop yields as an approximation of the GHGE offset CV, and (ii) Use the EPIC simulation under various weather scenarios and various regions, and find the GHGE offset CV.

Crop Yield CV as Proxy of GHGE Offset CV

As pointed out in Chapter VI, the CV of the GHGE offset cannot be easily found because data on sequestration histories of many parcels of the land in the project area is unavailable. We will use the crop yield as a proxy variable of the quantity of carbon offset because the carbon input is proportional to plant size, which is proportional to yield (Kimble). An examination of EPIC results shows that the correlations between sequestration rate and crop yields are very high ranging from 0.7 to 0.9 and these are statistically significant.

As given in equation (56) in Chapter VI, the CV for GHGE offset can be found using the CV for crop yield such that $CV_Q = CV_Y / R$ where R is the square root of the coefficient of determination (R^2) from the regression fitting[16]. It is noteworthy that we have only soybean, sorghum and rice simulation results which have both GHGE offset and yield data. Thus we use an average of R^2, which is 0.57. This implies that the correlation coefficient is 0.75. The CV for crop yield can be found from various USDA sources, mainly, database on the Economic Research Service web available at http://www.ers.usda.gov/data/psd/.

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[16] As argued in Chapter VI, intercept term in regression should be zero to use this formula to find the CV for GHGE offset. Most of regression results show that intercept term is zero statistically.

In empirically estimating examining uncertainty, we use yield data for 6 regional crops - sorghum, corn, rice, wheat, upland cotton and soybean from 1990 to 2001. Table 20 contains CVs for U.S., state, district and county level yield data. As we expect, aggregation across space reduces the CV. In case of soybeans, the CV for the U.S. is 7.0%, the CV for Texas is 15.6%, and the CV for a substate region (district 9 in Texas which consists of 13 counties) is 18.1% and the CV at the county level (Brazoria county in District 9 in Texas) is 23.1%.

From CVs for crop we can find the CV for GHGE offset using equation (56), that is, multiply by 1/R to the CV for crop yield, which is 1.32 ($= 1/\sqrt{0.57}$). Thus, the CV for GHGE offset is inflated about 32%. We don't report the CV for GHGE offset here, because there are two difficulties in selection of regional scale and crop which is the best proxy for the CV for GHGE offset. This will be discussed in the subsequent section.

Table 20. CV for Yield Over Space (1990 – 2001) (Unit: %)

	Sorghum	Corn	Rice	Wheat	Upland Cotton	Soybean
US	8.8	10.0	5.2	7.1	8.1	7.0
State (TX)	10.4	11.0	7.5	11.2	9.0	15.6
Ag. District (District 9, TX)	17.0	25.2	7.4*	25.0	23.4	18.1
County (Brazoria, TX)**	21.4	26.3	14.2	N/A	31.1	23.1

* Rice production area is mainly located in District 9 so that CVs for state and for agricultural district are very similar.

** Brazoria county is selected because this county cultivates various crops. Most of counties in the Southeast Texas area cultivate only rice, soybean and sorghum.

To see the effects of time on the CV, we assume a 5-year GHGE offset agreement, that is, we monitor the quantity of GHGE offset in 5 years. In this case, we need to find the CV using five year moving average. Table 21 contains CVs for 5-year moving average offsets evaluated at each regional scale showing that aggregation over time reduces the CV as we expect. In case of soybeans, the CV or 5 year cumulative yield at the US level is 2.5%, while it is 3.9% for Texas, 5.4% for district 9 and 8.7% for the county.

EPIC Simulation

We can use EPIC to generate a GHGE offset density function. EPIC1015 is used to simulate the GHGE offset rates over 25 years in the Southeast Texas area under various weather scenarios, which is the source of variability in GHGE offset rates. Figure 12 depicts the carbon inventory changes from the EPIC results under various weather scenarios in the specific area.

Table 21. CV for Yield Over Time[*] (5 year interval): (Unit: %)

	Sorghum	Corn	Rice	Wheat	Upland Cotton	Soybean
US	1.3	4.6	2.0	4.3	1.5	2.5
State (TX)	3.3	2.8	2.2	5.2	3.3	3.9
Ag. District (District 9, TX)	2.9	6.0	2.3	5.7	5.9	5.4
County (Brazoria, TX)	5.1	8.6	5.3	N/A	13.9	8.7

* The CV under 5-year agreement is the CV of five year moving averages for each crop at each level of aggregation.

In order to develop realistic weather scenarios, we need to use other weather station information. For example, we can use the weather information in North of Texas for dryer growing season scenario when we simulate the Southeast Texas area. We select 7 weather stations for generating various weather series[17], and then we run EPIC to generate the GHGE offset of pastures on low erosive soil over time on the one of county in the Southeast Texas area (Brazoria county).

The net GHGE offset flux is obtained difference between two successive estimates of inventory such that (Smith and Heath):

$$\text{(67)} \qquad \text{Rate of SOC/ac/yr} = \text{Inventory}_t - \text{Inventory}_{t-1}$$

Figure 12 depicts carbon inventory over time under various weather scenarios from EPIC simulations.

In turn, EPIC is run to estimate the GHGE offset rates over 25 years under various regions in Southeast Texas area[18] under assumptions that are the Conroe weather applies to all locations, same soil type (low erosive soil), and same management option (pasture) to see the spatial scale aggregation. Figure 13 depicts the carbon inventory changes in each region from the EPIC results over 5 regions in the Southeast Texas area under the same weather forecast.

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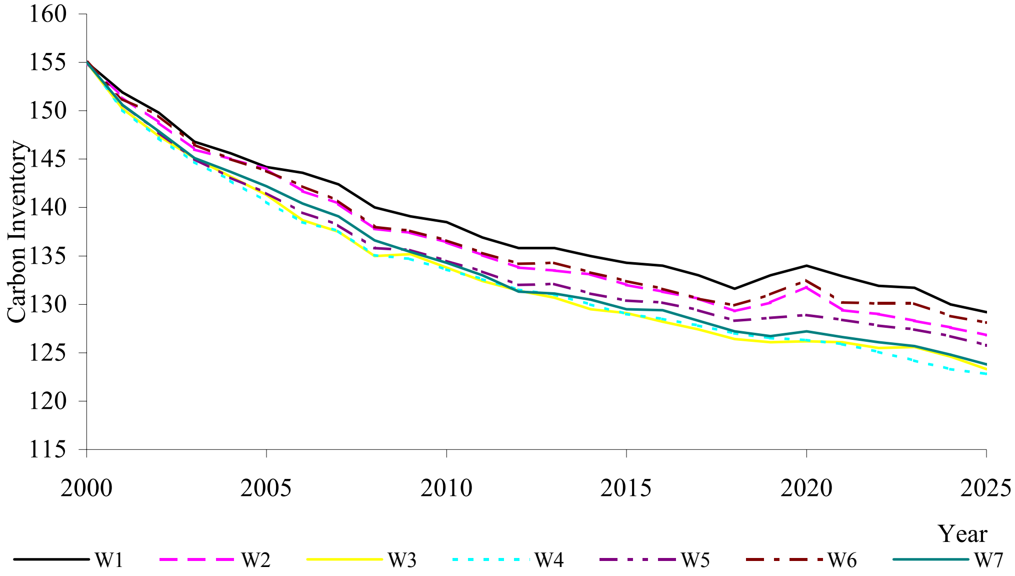
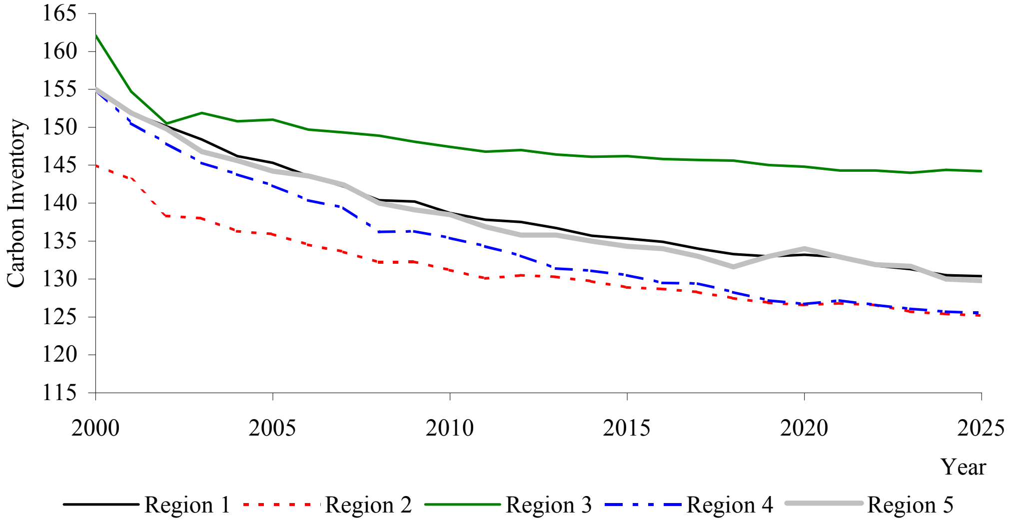
[17] We use following scenarios: (1) dryer and cooler growing season (Stratford, Dimmit, Seminole (weather stations in North)), (2) mild growing season (Coleman, Conroe (weather stations in Central)), and (3) wetter and hotter growing season (Liberty, and Anahuac (weather stations in Southeast)).

[18] We select 5 regions such as Grimes, Liberty, Colorado, Harris, and Brazoria counties which are located in the Southeast Texas.



Note: W1, W2 – Wetter season (weather in Southeast); W3, W4, W5 – Dryer season (weather in North); and W6, W7 – mild season (weather in Central)

Figure 12. Carbon inventory changes of pasture on low erosive soil under various weather scenarios from EPIC simulations over time



Note: R1 – Liberty, R2 – Grimes, R3 – Colorado, R4 – Harris, and R5 – Brazoria

Figure 13. Carbon inventory changes of pasture on low erosive soil of various regions from EPIC simulations

Table 22 contains CVs for five year moving average over each weather scenario and region after generating the simulated GHGE offset rates. As shown in Table 22, the CV of the GHGE offset rate for the specific region is presumed to be 15.3% which is an average of 7 CVs under various weather scenarios. If we consider 5-year GHGE contract, then the CV for the simulated GHGE offset rate decreases to 10.2%.

We can see the aggregation effect across regions in Table 22. The CV for aggregation over regions is computed as 9.4%. As we expected, the aggregation over space reduces the CV while the CV for individual region varies 13.6% ~ 36.0%

Estimation of Uncertainty Discount

We need to estimate the uncertainty discount needed to attain a given confidence interval. Assume that GHGE credits should be claimed with 95% certainty. The GHGE credit buyer is interested in more certain measure of offset volume than the mean.

Table 22. CV for GHGE Offset Rates from EPIC Simulations: (Unit: %)

	Region 1 under various weather							
	W1	W2	W3	W4	W5	W6	W7	Average
CV	12.9	13.6	17.0	16.9	17.0	14.2	15.4	**15.3**
CV for 5-year	7.2	7.2	13.2	12.7	13.1	7.4	11.0	**10.2**
	Various Regions under weather 1							Aggregation Over regions
	R1	R2	R3	R4	R5			
CV	15.2	23.3	36.0	17.5	13.6			**9.4**
CV for 5-year	10.9	12.0	21.8	10.8	7.3			**5.6**

Note: W1, W2 – Wetter season (weather in Southeast); W3, W4, W5 – Dryer season (weather in North); and W6, W7 – mild season (weather in Central)
R1 – Liberty, R2 – Grimes, R3 – Colorado, R4 – Harris, and R5 - Brazoria

We assume that sample size is sufficient to use normal density so that t^* would be 1.64 with 95% confidence band. However, there are two difficulties when we estimate *UNCER*: (i) selection of regional scale and (ii) selection of crop of the best proxy for *Q* when we use crop yields CVs. We will use an agricultural district as a regional scale with 5-year GHGE offset agreement, because the AO project is likely to be implemented in several counties and with a multi year contract. Also we will select the average of the CVs for crop yields as the proxy for variability in *Q* which is 4.7%. In this case, *UNCER* is computed as 10.2% ($= t^* \times 1/R \times \mathrm{CV} = 1.64 \times 1.32 \times 4.7\%$) with 95% confidence band.

If we utilize the results from the EPIC simulation, *UNCER* would be 9.2% ($= 1.64 \times 5.6\%$) under aggregation across several reasons with a multi year contract. We use an average of both *UNCER* estimates as the *UNCER* for the AO project, which is 9.7% ($= (10.2\% + 9.2\%)/2$).

Uncertainty Discount and Implication

UNCER is approximated as 9.7% with 95% confidence band. This implies that around 10 units out of 100 units of *Q* cannot be salable. If we decrease the confidence band to 90%, then *UNCER* decreases to 7.6%.

GHGE Credits

It is interesting to compute the quantity of salable offsets created by adopting the AO project after considering all the discounts. This is reported in Table 23. Scenario F1 has the largest GHGE credit which is 77.5% of the total GHGE offset. The lowest scenario is A1 scenario under rice to other crops conversion which is only 38.9% of the total GHGE offset. Approximately, afforestation can claim 70% of total GHGE offset as a credit, pasture can claim 55% of total GHGE offset as a credit and rice to other crops conversion can claim 40% of total GHGE offset as a credit.

Note that the additionality and the leakage discounts play an important role in computing the GHGE credits in case of a conversion to other crops but less so pasture conversions and even less for forest conversions. The permanence discount is important when for soils and short rotation forestry. Thus, scenarios which allow reverting back to the pre-AO practice have the large permanence discounts such as crop mix A1, pasture A1 and F3.

Table 23. GHGE Credit as Percent of Total Quantity of GHGE Offset for Each Alternative

		ADD (%)	LEAK (%)	PERM (%)	UNCER (%)	**GHGE Credit % of total QGHGO**
Rice to	A1	27.3	38.5	3.7	9.7	**38.9**
Crop Mix	A2	27.3	38.5	0.0	9.7	**40.4**
Rice to	A1	13.4	17.9	29.7	9.7	**45.1**
Pasture	A2	13.4	17.9	0.0	9.7	**64.2**
Rice to	F1	2.8	11.7	0.0	9.7	**77.5**
Forest	F2	2.8	11.7	3.1	9.7	**75.1**
	F3	2.8	11.7	31.9	9.7	**52.8**
	F4	2.8	11.7	9.2	9.7	**70.4**
	F5	2.8	11.7	11.6	9.7	**68.5**
	F6	2.8	11.7	7.1	9.7	**72.0**

CHAPTER VIII

SUMMARY AND CONCLUSIONS

This dissertation analyzes the role and implications of discount factors that might be applied to the GHGE mitigation projects, largely concentration on Agricultural Offset (AO) activities. The analysis focuses on theoretical and empirical approaches regarding the motivation for estimation of and incorporation of discount factors. Note that these discount factors are basically imposed by credit purchasers due to noncompliance with regulatory programs of some part of the credits with GHG program including consideration of shortfall penalties and limited duration.

The discount factor allows comparison of mitigation strategies when they consider multiple GHG mitigation possibilities. In this context, it is important to figure out how much GHGE offset can be really created by an AO project. Also, government or regulatory agencies who supervise and/or facilitate GHGE credit trading internationally or domestically would want estimates of the creditable amount given an offset possibilities. Discount factors are proposed for (i) additionality, (ii) leakage, (iii) permanence, and (iv) uncertainty.

Additionality concerns arise when the region where a sequestration project is being proposed would have substantial adoption of the AO practice in the absence of GHG programs. Additionality generally reduces the quantity of GHGE offset (Q). In other words, most of additionality is positive and salable GHGE offset reduces. In some cases, additionality may make the GHGE offset larger if normal actions would have increased GHGE.

In order to examine additionality, we propose a project-based approach and to do this, the prediction of land use is very important. In this study, two methods are proposed: (i) a Markov model and (ii) a Land share model. According to the empirical examination in Southeast Texas area, the additionality discount is computed to be 27.3% when rice to other crops project is adopted, 13.4% when rice lands are converted to pasture lands. When producers convert their rice fields to forestlands, the additionality discount is estimated to be 2.8%. In case of afforestation, this implies that 97.2% of the total GHGE offset created by afforestation can be claimed as a GHGE credit.

Leakage arises when the effect of a program is offset by an induced increase in economic activity and accompanying emissions elsewhere. The leakage effect may be substantial because both demand and supply elasticity are inelastic for agricultural product. We propose a formula to calculate the leakage discount that consisting exogenous variables such as elasticities, carbon sequestration rates and initial land allocations under multi-land use consideration.

In case of conversion of rice lands to other crops in Southeast Texas area, we find the leakage discount of 38.5%. This implies that the salable GHGE offset is reduced by 38.5% because of additional GHGE in other areas. In case of conversion of rice lands to pasture and afforestation, the leakage discounts are computed to be 17.9%, and 11.7%, respectively.

The permanence discount reflects the saturation and volatility characteristics of carbon sequestration. The year of saturation for tillage changes depends on soil, climate and many other factors but may be largely achieved around 20 years. In forestry case, it is around 80 years. Carbon is stored in a volatile form and can be released quickly to the atmosphere when an AO practice is discontinued and system reverts back to the pre-AO practice equilibrium.

The permanence discount depends on the AO project design including aspects of practice continuation, forest harvest, management, and replanting decisions after the AO program is over. Also, consideration of multiple offsets is important because the AO project could involve other GHGE offsets such as reductions in emissions of CO_2, CH_4 and N_2O, which are permanent GHG removal. In this case, the permanence discount is smaller compared with the permanence discount for the single offset case.

We assume a 100-year time horizon, 4% constant interest rate and alternative cases for harvesting management. Based on such assumptions, there are 2 cases for conversion to other crops or pasture and 6 cases for afforestation. Most of the permanence discounts are positive which vary from 0.0% to 31.9%. Shorter rotations in forestry exhibit the large permanence discount.

The uncertainty discount arises due to the stochastic nature of project offset quantity. The uncertainty discount is discussed in Chapter VI and we adopt the simple definition that uncertainty is a lack of confidence in a expected GHGE offset quantity. For the purposes of this study we will assume the variability in the quantity of the GHGE offset can be proxied by the agricultural district level GHGE offset distribution on a multi year basis (we use 5 years). Also, we assume the variability in the quantity of the GHGE offset can be simulated using the EPIC model.

It is noteworthy that the uncertainty discount tends to be smaller the larger the size of the offset contract due to aggregation over space and time because the uncertainty discount is defined in terms of the coefficient of variation. With 95% confidence interval, the uncertainty discount is computed to be 9.7%.

The magnitude of these discounts is investigated in the Southeast Texas rice discontinuation study. Based on discussions, the additionality and the leakage discounts are found to play an important role in case of rice lands conversion to other crops but less so for pasture conversions and yet less for forest conversions. The permanence discount is important when converting to other crops and short rotation forestry. Thus, scenarios which allow reverting back to the pre-AO practice have the large permanence discounts such as crop mix A1, pasture A1 and F3.

When all discounts are considered, the GHGE credit is computed as a proportion of the total GHGE offset. Afforestation yields claimable credits amounting to between 52.8% and 77.5% of the total GHGE offset. When converting rice lands to pasture yields claimable credits from 45.1% to 64.2% of the total GHGE offset, while a conversion of rice lands to other crops yields claimable credits from 38.9% to 40.4%.

REFERENCES

Adams, R.M., B.H. Hurd, and J. Reilly. *Agriculture and Global Climate Change: A Review of Impacts to U.S. Agricultural Resources*. Pew Center on Global Climate Change, Washington DC, 1999.

Adams, R.M., C. Rosenzweig, R.M. Peart, J.T. Ritchie, B.A. McCarl, J.D. Glyer, R.B. Curry, J.W. Jones, K.J. Boote, and L.H. Allen. "Global Climate Change and U.S. Agriculture." *Nature* 345(1990):219–224.

Adar, Z., and J.M. Griffin. "Uncertainty and the Choice of Pollution Control Instruments," *Journal of Environmental Economics and Management* 3(1976):178–188.

Ahn, S., A.J. Plantinga, and R.J. Alig. "Predicting Future Forestland Area: A Comparison of Econometric Approaches." *Forest Science* 46(2000):363–376.

Anderson, D.P. *Texas Crop Enterprise Budgets: Southeast Texas District*, Texas Agricultural Extension Service, Texas A&M University System, U.S. Department of Agriculture and the County Commissioner Courts of Texas Cooperating, 2000.

Bell, E.J. "Markov Analysis of Land Use Change – An Application of Stochastic Processes to Remotely Sensed Data." *Journal of Socioeconomic Planning Sciences* 8(1974):311–316.

Ben-Akiva, M., and S.R. Lerman. *Discrete Choice Analysis: Theory and Application to Travel Demand*. The MIT Press, Cambridge, Massachusetts, 1985.

Birdsey, R.A. “Carbon Storage for Major Forest Types and Regions in the Conterminous United States.” Chapter 1 in Sampson, R. Neil and Dwight Hair (eds.), *Forests and Global Change, Vol. 2: Forest Management Opportunities for Mitigating Carbon Emissions*, American Forests, Washington, DC, 1996.

Birdsey, R.A., and L.S. Heath. “Carbon Changes in US Forests.” In: Joyce, L.A. (Ed.), *Productivity of America’s Forests and Climate Change*. General Technical Report RM – 271, USDA Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO, 1995.

Bohm, P. “On the feasibility of Joint Implementation of carbon emissions reductions, Climate Change: Policy Instruments and their Implications.” *Proceedings of the Tsukuba Workshop of IPCC Working Group III*, A. Amano ed., Center for Global Environmental Research, Environment Agency of Japan, Tsukuba, Japan, 1994.

Bourne, L.S. *Forecasting Land Occupancy Changes Through Markovian Probability Matrices: A Central City Example*. Research Report No. 14. Center for Urban and Community Studies, University of Toronto, Toronto, 1969.

Brooks, H.G., S.V. Aradhyula, and S.R., Johnson. “Land Quality and Producer Participation in US Commodity Programs.” *Review of Agricultural Economics* 14(1992):105–115.

Bruce, J.P., H. Lee, and H.F. Haites. *Climate Change 1995: Economic and Social Dimensions of Climate Change. Contribution of Working Group III to the Second Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press, New York, 1996.

Canada. “Methodological Issues, Inventories and Uncertainties.” United Nations Framework Convention on Climate Change, Subsidiary Body for Scientific and Technological Advice. Additional submissions by parties to the Ninth Session at Buenos Aires, 2-13 November 1998, Item 4 of the provisional agenda. Other Matters, Approaches to resolving methodological issues related to national communications from Annex I Parties, 1998. Available at http://www.unfccc.de/resource/docs/1998/sbsta/misc06a01.pdf

Chomitz, K.M. “Baselines for Greenhouse Gas Reductions: Problems, Precedents, Solutions.” prepared for the Carbon Offsets Unit, World Bank, *Draft for discussion: rev 1.4.16 July*,1998. Available at http://www.worldbank.org/nipr;/work_paper/base14/base14.pdf

Chomitz, K.M. “Baseline, Leakage and Measurement Issues: How Do Forestry and Energy Projects Compare?” *Climate Policy* 2(2002):35–49.

Cullen,A.C., and H.C. Frey. *Probabilistic Techniques in Exposure Assessment*. Plenum Press, New York, 1999.

Dasgupta, P., P.J. Hammond, and E. Maskin. “A Note on Imperfect Information and Optimal Pollution Control,” *Review of Economic Studies* 47(1980):857–860.

Dixon, R.K., K.J. Andrasko, F.G. Sussman, M.A. Lavinson, M.C. Trexler, and T.S. Vinson. “Forest Sector Carbon Offset Projects: Near-Term Opportunities to Mitigate Greenhouse Gas Emissions.” *Water, Air and Soil Pollution* 70(1993):561–577.

Dobes, L., I. Enting, and C. Mitchell. “Accounting for carbon sinks: The problem of time.” Dobes, L. ed. *Trading Greenhouse Emissions: Some Australian Perspectives*, Bureau of Transport Economics, Canberra, Australia, 1998.

Dubois, M.R., C.B. Erwin, and T.J. Straka. “Costs and Cost Trends for Forestry Practices in the South.” *Forest Landowner* 60(2001):3–8.

Feng, H., J. Zhao, and C.L. Kling. “The Time Path and Implementation of Carbon Sequestration.” *American Journal of Agricultural Economics* 84(2002):134–149.

Fearnside, P.M. “Global Warming Response Options in Brazil’s Forest Sector: Comparison of Project-Level Costs and Benefits.” *Biomass and Energy*, 8(1995):309–322.

Fearnside, P.M. “Greenhouse-Gas Emissions From Amazonian Hydroelectric Reservoirs—the Example of Brazil’s Tucurui Dam as Compared to Fossil Fuel Alternatives.” *Environmental Conservation*, 24(1997):64–75.

Fearnside, P.M., D.A. Lashof and P. Moura-Costa. “Accounting for Time in Mitigation Global Warming through Land-Use Change and Forestry.” *Mitigation and Adaptation Strategies for Global Change* 5(2000):239–270.

Fischer, C. “Determining Project-Based Emission Baselines with Incomplete Information,” *Discussion Paper* 02-23, Resources for the Future, Washington DC, 2002.

Griffiths, W.E., R.C. Hill and G.G. Judge. *Learning and Practicing Econometrics*. John Wiley & Sons, New York, 1992.

Hardie, I.W., and P.J Parks. “Land Use with Heterogeneous Quality: An Application of an Area Base Model.” *American Journal of Agricultural Economics* 77(1997):299–310.

Hattis, D., and D.E. Burmaster. “Assessment of Variability and Uncertainty Distributions for Practical Risk Analyses.” *Risk Assessment* 14(1994):713–730.

Heath, L.S., and J.E. Smith. “An Assessment of Uncertainty in Forest Carbon Budget Projections.” *Environmental Science and Policy* 3(2000):73–82.

Herzog, H., K. Caldeira, and J. Reilly. “An Issue of Permanence: Assessing the Effectiveness of Temporary Carbon Storage.” *Climatic Change* 59(2003):293–310.

Hiller F.S., and G.J. Lieberman. *Introduction to Operation Research*. Fifth edition, McGraw Hill, Singapore, 1990.

Hoag, D.L., B.A. Babcock, and W.E. Foster. “Field-Level Measurement of Land Productivity and Program Slippage.” *American Journal of Agricultural Economics* 75(1993):181–189.

Holzapfel-Pschorn, A., R. Conrad, and W. Seiler. “Production, Oxidation, and Emission of Methane in Rice Paddies.” *FEMS Microbiology Ecology* 31(1985):343–351.

Houghton, J.T., Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell, and C.A. Johnson. *Climate Change 2001: The Scientific Basis.* Cambridge University Press, Cambridge, England, 2001.

Intergovernmental Panel on Climate Change (IPCC). *IPCC Special Report on Land Use, Land Use Change and Forestry*. R.T. Watson, I.R. Noble, B. Bolin, N.H. Ravindranath, D.J. Verardo, D.J. Dokken (Eds), 2000. Available at http://www.grida.no/climate/ipcc/land_use/index.htm

Izaurralde, R.C., J.R. Williams, W.B. McGill and N.J. Rosenberg. “Simulating Soul Carbon Dynamics, Erosion and Tillage with EPIC.” Paper presented at the First National Conference on Carbon Sequestration organized by the U.S. Department of Energy, Washington DC, May 14 – 17, 2001.

Joos, F., M. Bruno, R. Fink, U. Siegenthaler, T. Stocker, C. Le Quere, and J.L. Sarmiento. “An Efficient and Accurate Representation of Complex Oceanic and Biospheric Models of Anthropogenic Carbon Uptake.” *Tellus* 48(1996):623–637.

Judge, G.G., R.C. Hill, W.E. Griffiths, H. Lutkepohl, and T.C. Lee. *Introduction to the Theory and Practice of Econometrics*. John Wiley & Sons, New York, 1988.

Kimble, J.M. “Private Communication Based on Carbon Sequestration and Crop Yield.” In the Energy Agriculture Forum in CASMGS, College Station, TX, January, 2004.

Lal, R., L.M. Kimble, R.F. Follett, and C.V. Cole. *The Potential of U.S. Cropland to Sequester C and Mitigate the Greenhouse Effect*. Ann Arbor Press, Chelsea, MI, 1998.

Lee, H.C., B.A. McCarl, U.A. Schneider and C.C. Chen. “Economic Implications of International participation Alternatives for Agricultural Greenhouse Gas Emission Mitigation.” Paper presented at Taiwan Conference on Carbon Sequestration, November 2000.

Lee, K., F. Kaiser, and R. Alig. "Substitution of Public for Private Funding in Planting Southern Pine." *Southern Journal of Applied Forestry* 16(1992):204–208.

Lichtenberg, E. "Land Quality, Irrigation Development, and Cropping Patterns in the Northern High Plains." *American Journal of Agricultural Economics* 71(1989):187–194.

Lubowski, R., A.J. Plantinga, and R.N. Stavins. "A National-Level Econometric Analysis of the Costs of Carbon Sequestration." Prepared for Presentation at the Forestry and Agriculture Greenhouse Gas Modeling Forum, Shepherdstown, WV, 2001.

Marland, G., K. Fruit, and R. Sedjo. "Accounting for Sequestered Carbon: The Question of Permanence." *Environmental Science and Policy* 4(2001):259–268.

Marland, G., and B. Schlamadinger. "The Kyoto Protocol Could Make a Difference for the Optimal Forest-Based CO2 Mitigation Strategy: Some Results from GORCAM." *Environmental Science and Policy* 2(1999):111–124.

McCarl, B.A., B. Murray and J. Antle. "Agricultural Soul Carbon Sequestration: Economic Issues and Research Needs." Draft Paper #875, Department of Agricultural Economics, Texas A&M University, College Station, TX, 2002.

McCarl, B.A., and U.A. Schneider. "Agriculture's Role in a Greenhouse Gas Emission Mitigation World: An Economic Perspective." *Review of Agricultural Economics* 22(2000):134–159.

McCarl, B.A., and U.A. Schneider. “The Cost of Greenhouse Gas Mitigation in U.S. Agriculture and Forestry.” *Science* 294(2001):2481–2482.

McCarthy, J.J., O.F. Canziani, N.A. Leary, D.J. Dokken, and K.S. White. *Climate Change 2001: Impacts, Adaptation, and Vulnerability*. Cambridge University Press, Cambridge, England, 2001.

McConkey, B., and C.W. Lindwall. “Measuring Soil Carbon Stocks – A system for Quantifying and Verifying Change in Soil Carbon Stocks due to Changes in Management Practices on Agricultural Land.” Presentation prepared for special seminar, UNFCCC, SBSTA, Bonn, Germany, June 1999. Semiarid Prairie Agricultural Research Centre, Swift Current, Saskatchewan, 1999.

Mendelsohn, R., W. Nordhaus, and D. Shaw. “The Impact of Global Warming on Agriculture: A Ricardian Analysis.” *American Economic Review* 84(1994):753–771.

Miller, D.J., and A.J. Plantinga. “Modeling Land Use Decisions with Aggregate Data.” *American Journal of Agricultural Economics* 81(1999):180–194.

Millock, K, D. Sunding, and D. Zilberman, “Regulating Pollution with Endogenous Monitoring,” *Journal of Environmental Economics and Management* 44(2002):221–241.

Moore, D.S., and G. P. McCabe. *Introduction to the Practice of Statistics*. 2nd Edition, W.H. Freeman and Company, New York, 1993.

Morgan, M. G., and M. Henrion. *Uncertainty: A Guide to the Treatment of Uncertainty in Quantitative Policy and Risk Analysis*. Cambridge University Press, New York, 1990.

Moura-Costa, P.H. "Tropical Forestry Practices for Carbon Sequestration." – Schulte, A and D. Schone (Ed.), *Dipterocarp Forest Ecosystems—Towards Sustainable Management*. World Scientific, Singapore, 1996.

Moura-Costa, P.H. *Carbon Accounting, Trading and the Temporal Nature of Carbon Storage*. The Nature Conservancy, U.S. Agency for International Development (USAID), Washington, DC, 2002.

Muller, M.R. and J. Middleton. "A Markov Model of Land-Use Change Dynamics in the Niagara Region, Ontario, Canada." *Landscape Ecology* 9(1994):151–157.

Murray, B.C. *Alternative Methods for Establishing Carbon Baseline: Afforestation of Mississippi Bottomland Hardwoods*. Presented at Forestry and Agricultural Greenhouse Gas Modeling Forum, Shepherdstown, WV, 2002.

Murray, B.C., B.A. McCarl, and H.C. Lee. "Estimating Leakage From Forest Carbon Sequestration Programs." *Land Economics* 80(2004):109–124.

National Academy of Sciences. *Policy Implications of Greenhouse Warming: Mitigation, Adaptation, and the Science Base*. Washington DC, National Academy Press, 1992.

Newey,W., and West K. "A Simple, Positive Semi-definite, Heteroskedasticity and Autocorrelation Consistent Covariance Matrix," *Econometrica* 55(1987):703–708.

Noble,I., M. Apps, R. Houghton, D. Lashof, W. Makundi, D. Murdiyarso, B. Murray, W. Sombroek, and R. Valentini. "Implications of Different Definitions and Generic Issues," In Watson, R.T., I. Noble, B. Bolin, N.H. Ravindranath, D.J. Verado, and D.J. Dokkens. (Ed.), *Land Use, Land Use Change, and Forestry*, Cambridge University Press, Cambridge UK (2000):53–156.

Parks, P.J., and I.W. Hardie. "Least-Cost Forest Carbon Reserves: Cost-Effective Subsidies to Convert Marginal Agricultural Land to Forest." *Land Economics* 71(1995):122–136.

Plantinga, A.J., and R.A. Birdsey. "Carbon Fluxes Resulting from US Private Timberland Management." *Climatic Change* 23(1993):37–53.

Plantinga, A.J., and J. Wu. "Co-Benefits from Carbon Sequestration in Forests." *Land Economics* 79(2003):74–85.

Post, W.M., and K.C. Kwon. "Soil Carbon Sequestration and Land-Use Change: Processes and Potential." *Global Change Biology* 6(2000):317–328.

Ramos, M.G. *Texas Almanac: 2000 – 2001*. The Dallas Morning News, Distributed by Texas A&M University Press, 1999.

Rausmussen, P.E., W.J. Parton. "Long-term Effects of Residue Management in Wheat Fallow: Inputs, Yield and Soil Organic Matter." *American Journal of Soil Science* 58(1994):523–530.

Reddy, S., and C. Price. "Carbon Sequestration and Conservation of Tropical Forests under Uncertainty." *Journal of Agricultural Economics* 50(1999):17–35.

Richards, K.R. “The Time Value of Carbon in Bottom-up Studies.” *Critical Reviews in Environmental Science and Technology* 27(1997):S279–S292.

Roberts, M.J., and M. Spence. “Effluent Charges and Licenses under Uncertainty,” *Journal of Public Economics* 5(1976):193–208.

Sampson, R.N., and R.A. Sedjo. “Economics of Carbon Sequestration in Forestry: An Overview.” *Critical Reviews in Environmental Science and Technology* 27(1997):S1–S8.

Sass, R.L., F.M. Fisher, P.A. Harcombe, and F.T. Turner. “Methane Production and Emission in a Texas Rice Field.” *Global Biogeochemical Cycles* 4(1990):47–68.

Seton's EH&S Compliance Resource Centers. Chapter I – Part 77, *40-CFR Protection of Environment* (2003). Available at http://www.setonresourcecenter.com/40CFR/Docs/wcd0007c/wcd07c1a.asp

Shortle, J.S., and J.W. Dunn. “The Relative Efficiency of Agricultural Source Water Pollution Control Policies,” *American Journal of Agricultural Economics* 68(1986):668–677.

Smith, J.E., and L.S. Heath. “Identifying Influences on Model Uncertainty: An Application Using a Forest Carbon Budget Model.” *Environmental Management* 27(2001):253–267.

Smith, R.B.W., and T.D. Tomasi. “Transaction Costs and Agricultural Nonpoint-Source Water Pollution Control Policies,” *Journal of Agricultural and Resource Economics* 20(1995):277–290.

Stavins, R.N., and A. Jaffe. “Unintended Impacts of Public Investment on Private Decisions: The Depletion of Forest Wetlands.” *American Economic Review* 80(1990):337–352.

Tipper, R. and B.H. de Jong. “Quantification and regulation of carbon offsets from forestry: Comparison of alternative methodologies, with special reference to Chiapas, Mexico.” *Commonwealth Forestry Review* 77(1998):219–228.

United Nations. “United Nations Framework Convention on Climate change.” 1992. Available at http://unfccc.int/resource/docs/convkp/conveng.pdf

United Nations Framework Convention on Climate Change (UNFCCC). *Kyoto Protocol to the United Nations Framework Convention on Climate Change*. UNFCCC Secretariat, Bonn, 1998.

United States Department of Agriculture (USDA). *1997 Census of Agriculture.* National Agricultural Statistics Service (NASS), USDA, March 1999.

United States Department of Agriculture (USDA). *Rice Situation and Outlook Yearbook*. Market and Trade Economics Division, ERS, USDA, RCS-2001, 2001.

United States Department of Agriculture (USDA), Economic Research Service, Annual data on international production, yields, and harvested acreage as compiled on the ERS web, 2002. Available at http://www.ers.usda.gov/data/psd

United States Department of Commerce (USDOC). *1992 Census of Agriculture*. Economics and Statistics Administration, Bureau of the Census, USDOC, October 1994.

United States Department of States (USDOS). *United States Submission on Land-Use, Land-Use Change, and Forestry*. August 2000. Available at http://www.usda.gov/oce/oce/complete.doc.

United States Environmental Protect Agency (US EPA). “Method for Estimating Methane Emission from Flooded Rice Fields.” Chapter 8 in *Estimating Greenhouse Gas Emission, Emission Inventory Improvement Program (EIIP)* Document Series – Volume VIII, 1999. Available at http://www.p2pays.org/ref/17/ttn/volume08/viii08.pdf.

United States Environmental Protect Agency (US EPA). *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 – 1999.* Office of Atmospheric Program (6204N), EPA 236–R–01–001, April 2001. Available at http://www.epa.gov/globalwarming/emissions/national.

United States Environmental Protect Agency (US EPA). Data and Formulas for Calculation of CO2 Emission from Fossil Fuel Usage as compiled on the EPA web, 2003. Available at http://www.epa.gov/region4/air/cai/formulas_main.htm

Waldman, D.M., and M.T. Ozog. “Natural and Incentive-Induced Conservation in Voluntary Energy Management Programs.” *Southern Economic Journal* 62(1996):1054–1071.

Weisstein, E.W. "Correlation Coefficient." *MathWorld*, A Wolfram Web Resource, 2004. Available at mathworld.wolfram.com/CorrelationCoefficient.html

Weitzman, M. “Optimal Rewards for Economic Regulation,” *American Economic Review* 68(1978):683–691.

West, T.O., and W.M. Post. “Soil Organic Carbon Sequestration Rates by Tillage and Crop Rotation: A Global Data Analysis.” *Soil Science Society of America Journal* 66(2002):1930–1946.

White, H. “A Heteroskedastcity-Consistent Covariance Matrix Estimator and a Direct Test for Heteroskedasticity.” *Econometrica* 48(1980):817–838.

White House. Press Briefing by Ari Fleischer, Office of the Press Secretary, March 28, 2001. Available at http://www.whitehouse.gov/new/briefings/20010328.html

White House. “Global Climate Change Policy Book.” February 2002. Available at http://www.whitehouse.gov/news/releases/2002/02/climatechange.html

Williams, J.R., C.A. Jones, K.R. Kiniry, and D.A. Spaniel. “The EPIC Crop Growth Model.” *Transactions of The American Society of Agricultural Engineers* 32(1989):497–511.

Wu, J. “Slippage Effects of the Conservation Reserve Program.” *American Journal of Agricultural Economics* 82(2000):979–992.

Wu, J., and K. Segerson. “The Impact of Policies and Land Characteristics on Potential Groundwater Pollution in Wisconsin.” *American Journal of Agricultural Economics* 77(1995):1033–1047.

Xu, Weihuan. *Harvest Trends 2001*. Texas Forest Resource, Texas Forest Service, The Texas A&M University System, Publication 163, 2002.

Zelek, C.A. and G.E. Shively. “Measuring the Opportunity Cost of Carbon Sequestration in Tropical Agriculture.” *Land Economics* 79(2003):342–354.

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