ESSAYS ON RISK AND UNCERTAINTY IN GREENHOUSE GAS TRADING MARKETS

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ABSTRACT

A large number of concepts related to carbon offset trading policy are currently being discussed such as baseline, leakage, permanence, monitoring, verification, enforcement, financial feasibility, and third party verification. Cutting across these concepts are a variety of risks and uncertainties. These risks play a major role in developing effective market designs that achieve aggregate emission caps while encouraging market participation and investment in carbon reduction activities. What are the risks associated with carbon offset policy and how do such risks affect incentives for investing in carbon offsets?

A literature review of carbon trading risks is developed. Risks associated with carbon offsets policy can be classified into three major categories: institutional/policy, project level and measurement risks. Institutional/policy risks are related to uncertainties surrounding the future policy decisions and the institutional arrangements established to define baselines, stipulate monitoring/enforcement requirements, and define and estimate leakage. Baseline estimates are necessary to calculate the net carbon reduction of a program or project. Monitoring/enforcement risk is associated with the regulators' ability to detect whether the promised carbon sequestration activities are undertaken. Leakage occurs when carbon sequestration at one site encourages increase in carbon emissions on some other site. Project risk refers to non-performance of a carbon sequestration project in terms of not achieving the requisite target of carbon sequestration. Project risk includes physical risk and financial risk. Physical risks are associated with unexpected carbon emissions due to natural hazards or events such as fire, or hurricanes or changes in the rate of sequestration, which depend on weather and pests. Landowners will not participate in carbon sequestration programs if they expect to incur financial losses by participating. Measurement risk arises because it is difficult to measure actual rates of carbon sequestered due to spatial and temporal heterogeneity of carbon present in agricultural and forest production.

Forests are a principal carbon 'sink' for sequestering carbon from the atmosphere. The provision of trading emission rights under the Kyoto Protocol will provide forest landowners the opportunity to reap financial gains from sequestering carbon and trading rights to emit carbon in carbon permit markets. However, landowners may be liable for repaying all or some of the proceeds received for sequestering carbon if stored carbon is released during the contract period. Hurricane damage to forests may cause extensive mortality and subsequent emission of carbon dioxide from decomposing biomass. Such liabilities may reduce landowners' incentives to sequester carbon. This research

evaluates incentives of an individual forest landowner for sequestering and trading carbon, given the risk of carbon loss from hurricanes. Results of our simulation model reveal that the effect of hurricane risk on landowners' behavior depends on the variability of returns from carbon and timber and the ability of landowners to mitigate risk by diversifying forest holdings across regions with different sequestration rates and different hurricane strike probabilities.

Some risk mitigation strategy might be required to create the necessary incentives for landowner participation especially in hurricane prone regions. We evaluate incentives of forest landowners for sequestering and trading carbon, given the risk of carbon loss from hurricanes, and an opportunity to insure their losses. Results of simulation model reveal that the effect of hurricane risk depends on the variability of returns from carbon and timber and landowners' ability to mitigate risk by diversifying forest holdings across regions or transferring risk by purchasing insurance. Although, landowner can spread the risk of carbon loss by diversifying into different regions, insurance has a role to play over and above diversification by reducing landowners' risk (variance) from forestry investments for sequestration and timber purposes, even when timber losses are not insured.

Dedication

I dedicate this work to my parents, Mrs. and Lt. Col. Vijay Kumar. Any accomplishments of mine are due in no small part to their love, support and guidance during my many, many years as a student. Their lessons of hard work and perseverance have served me well, and have culminated in these pages. I also dedicate this work to my beloved husband Amrish Vyas whose caring support, love and encouragement saw through the completion of this dissertation.

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Chapter I

INTRODUCTION

Amplification of international concern over upsurge of greenhouse gases, principally carbon dioxide, in the Earth's atmosphere has brought a number of opportunities for greenhouse gas reduction into the forefront. One of the key strategies for mitigating climate change entails changes in management of land use. The 'Third Conference of the Parties' (COP) to the Framework Convention on Climate Change (FCCC) in Kyoto in 1997, which resulted in the Kyoto Protocol, brought into focus the possibility of adopting changes in land use management to take advantage of the fact that carbon can accumulate in vegetation and soils in terrestrial systems. The Kyoto Protocol represents by far the most concerted effort towards building a global consensus on the need for mitigating anthropogenic greenhouse gas (GHG) emissions. The Kyoto Protocol, agreed upon by 159 nations that attended the 3rd COP to the United Nations Convention on Climate Change in Kyoto, Japan in December of 1997, specifies the deadlines and specific levels of greenhouse gas reductions that signatory countries are to achieve. Overall, developed countries are to reduce greenhouse gas emissions by 5.2% between 2008 and 2012 as measured against their 1990 emission levels.

Though the Protocol is yet to be ratified by the United States, it has prompted some potential buyers and sellers to seek new and innovative approaches to reduce net carbon emissions, especially through terrestrial sequestration, not only within U.S. but also in other parts of the world. "As of December 2001, about 20 voluntary carbon offset[1] trades have taken place that involve carbon sequestration[2] projects undertaken on U.S. forest and agricultural lands" (King, p. 1).

The Kyoto Protocol recognizes that removing carbon from the atmosphere can slow down the build-up of atmospheric carbon dioxide levels. This reduction in carbon dioxide build-up can be achieved either by reducing emissions from fossil fuel combustion or by changing land use management to take advantage of the fact that carbon can accumulate in vegetation and soils in terrestrial systems – an opportunity that was brought into focus at the Third Conference of the Parties (COP) to the Framework Convention on Climate Change (FCCC) in Kyoto (IPCC). Forests have been identified as key carbon sinks under the Protocol (Murray et al.). Schlamadinger and Marland (p. iii), referred to the opportunities to reduce the rate of build-up of atmospheric carbon dioxide (CO_2) through land management activities, as Land Use, Land-Use Change, and Forestry (LULUCF) activities. Various practices can be undertaken under LULUCF activities to generate carbon offsets, for instance, retarding the rate at which carbon is lost from plants and soils, e.g., through reduced rates of deforestation, and bolstering sequestration of carbon from the atmosphere to plants and soils, e.g., by afforestation and reforestation or improving management of forests or agricultural soils.

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[1] Offsets are a form of credit-based emissions trading. Offsets are created when a source makes voluntary, permanent emissions reductions that are in surplus to any required reductions. Existing sources that create offsets can trade them to new sources to cover growth or relocation. (http://www.co2e.com/common/glossary.asp#O)

[2] Carbon sequestration in terrestrial ecosystems can be defined as the net removal of CO2 from the atmosphere into long-lived pools of carbon. The pools can be living, aboveground biomass (e.g., trees), products with a long, useful life created from biomass (e.g., lumber), living biomass in soils (e.g., roots and microorganisms), or recalcitrant organic and inorganic carbon in soils and deeper subsurface environments. (http://www.fws.gov/southeast/news/2005/images/carbon-fact-sheet.pdf)

Various provisions contained in the Protocol that provide flexibility in meeting those targets include i) A five year commitment period from 2008-2012 allowing countries to delay or hasten emission reductions within the agreed upon time frame; ii) Incorporation of all six greenhouse gases[3] and allowing emissions reductions of one gas to be substituted for increases in emissions of another; iii) Use of certain carbon "sinks " (increased tree plantation, improved agricultural land management practices etc.) to achieve emission reduction targets; iv) International emissions trading and joint implementation[4] (JI) of projects among Annex I countries (countries with binding targets); and, v) Clean Development Mechanism[5] (CDM) that will allow industrialized countries to earn credits for funding emission reducing projects in Annex II countries (developing countries which do not face any emission constraints).

One of the options for meeting emissions reductions goals through the Protocol is trading of carbon offsets, including those created by land use change and forestry practices. Certified reductions in carbon emissions from forests, which are not required to reduce carbon emissions under a regulated program, can be used to generate "carbon offsets" that can be sold to other sectors as permits to meet mandatory or voluntary reductions in greenhouse gas emissions. Offset trading is a form of credit-based

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[3] The six greenhouse gases specified in the Kyoto Protocol are: Carbon dioxide (CO2), Methane (CH4), Nitrous oxide (N20), Hydrofluorocarbons (HFCs), Perfluorocarbons (PFCs) and Sulphur hexafluoride (SF6).

[4] Joint Implementation (JI) is a project-based mechanism developed under the Kyoto Protocol (KP), designed to assist Annex 1 countries in meeting their emission reduction targets through joint projects with other Annex 1 countries, meaning that JI projects can only be implemented between capped industrialized countries.

[5] A market mechanism defined in the Kyoto Protocol (Article 12) as a project between a developed country and a developing county that provides the developing country with the financing and technology for sustainable development and assists the developed country in achieving compliance with its emission reduction commitments. (www.climate.org.ua/glossary/glossary_c.html)

emissions trading, where offsets are created when a land-based source (more generally a source that faces no mandatory emission caps) makes voluntary reductions in emissions or increases sequestration activities. Carbon credit is carbon stored or sequestered in a carbon sink, which can be used by governments, or other entities, to offset greenhouse gas emissions (Enzinger and Jeffs).

The provision of trading emission rights under the Kyoto Protocol will provide GHG emitters a way to reduce costs of meeting emissions targets and will provide landowners the opportunity to reap financial gains from sequestering carbon and selling the rights to emit carbon. The term emission trading refers to the trading of property rights or certificates which represent a variety of ways in which carbon-related emission reduction targets might be met. Carbon trading can take on different forms whereby agents buy and sell contractual obligations or credits that represent specified amounts of carbon-related emissions 1) which may be emitted (McKibbin, Shackleton and Wilcoxen); 2) which may be abated (Gupta); or 3) which may represent offsets against emissions, such as carbon sequestration (capture of carbon in biomass) (Cairns and Lasserre).

“Once viewed as only a pipe dream of academic economists, the trading of environmental flows is being increasingly sought by policy makers to address a wide range of issues… The idea is catching on, and policy makers and economists alike are beginning to look at virtually every environmental problem and asking, "Can trading be used to solve this problem?"”(Woodward). Trading of environmental rights has been advocated by economists since the 1960’s, with one of the initial writings by Dales

(Dales) who first provided a conceptual and practical framework for the possibility of trading as a mechanism to deal with environmental problems. Potential benefits of pollution trading have been known for years and trading has been used under the sulfur dioxide trading program in the US. The sulfur dioxide trading is an allowance-based "cap and trade" program such that affected electric utility units are allocated allowances, based on their historic fuel consumption and specific emissions rate. Affected sources with a shortfall of allowances may buy them from sources that have reduced emissions below their allocated level. Unused allowances of a given vintage year may also be "banked forward" to the next or future years. If land-based carbon trading is established along with emission caps, it could improve air quality and/or lower costs of achieving air quality goals.

GHG emissions trading markets will have to be designed so as to provide sufficient incentives to induce landowners to participate in these markets because carbon sequestration is costly. In addition to the direct costs of undertaking activities to sequester carbon and the cost of market participation, there are costs associated with various risks and uncertainties that market participants might have to bear. Market and non-market risks and uncertainties may be in terms of uncertain political and institutional environment, uncertainty in measurement and verification/monitoring of proposed sequestration activities, uncertainty at the project level because of uncertain financial returns and the risk of carbon loss due to natural hazards including hurricanes, wild fires, insect infestations and diseases.

Risk and uncertainty in environmental markets may stem either from the demand side, or the supply side or they may be a result of institutional failure (King and Kuch). Demand for environmental goods like carbon offsets will be created when regulations set up a cap on overall industry emissions. Once the cap is established it might be challenge for the regulatory authority to assess the integrity of the 'commodity' being traded, in this case a carbon offset permit, such that the overall environmental goals are achieved. Demand for carbon offsets depends on the difference between the cost of on-site reduction in carbon dioxide emissions and the cost of buying enough carbon offsets to compensate for further emissions. There also exists the risk of non-delivery of carbon offsets, which might result in higher costs of entering into a carbon offset contract to reflect the physical risk (King and Kuch). The supply of carbon offsets will depend on the cost of creating them, baseline definition and compliance of sequestration practices with state and federal regulations. Both supply and demand of offsets might depend on the transactions costs; these include the costs of finding and negotiating with potential trading partners, monitoring sequestration activities, and validating results. The landowner must factor in the costs associated with accepting liability for physical risks if the landowner fails to perform sequestration activities, or if that activity does not result in the expected level of offsets, or if there are unexpended carbon losses.

Despite the possibility of non-permanence of carbon stored in forest sinks, there are benefits associated with temporary carbon storage, which postpone climate change and buy time for developing and discovering alternative technologies to abate fossil fuel emissions. The issue of non-permanence has been discussed mainly in relation to carbon offsets generated from projects based in non-Annex B countries (developing countries under the Kyoto Protocol), which are not expected to be under an emissions cap. However, non-permanence will be an important issue for offsets created from projects based in certain sectors such as forestry and agriculture, which are not obligated to reduce emissions in the Annex B countries (developed countries under a regulated emissions cap).

Given that the U.S. forests sequester carbon at a rate of 250 MMTC/yr, which is 15% of U.S. emissions (Reaves et al.), forest landowners stand to reap financial gains from producing and selling carbon offsets. There is a considerable gap, however, between sequestering an actual ton of carbon in forests, and having that ton available to be used as an offset by a carbon emitter operating under a regulated carbon abatement program. Included in the gap between "growing" a ton and "selling" a ton is the likelihood that the sequestered carbon may be emitted back into the atmosphere as a result of market regulations as well as non-market risks and uncertainties such as natural disasters like hurricanes or tornadoes. Landowners may be liable for repaying all or some of the proceeds received in the past for sequestering carbon and generating carbon offsets when forests are damaged by natural calamities, which cause extensive mortality and subsequent emission of carbon dioxide from decomposing biomass. Such risks could impose costs on sellers in terms of financial losses and penalties in an accounting scenario that holds carbon-offset producers liable for non-delivery within the contract period. These costs would be in addition to salvage costs and damage to timber, which is likely to reduce future returns from timber sales. If the costs and penalties are too high, landowners, especially small and/or risk averse landowners will simply avoid the carbon market. Information on the effects of risks on incentives to sequester carbon would be helpful to policymakers and program managers dealing with carbon trading proposals.

These costs may become a serious deterrent to decision makers who are risk averse. Without some form of risk management or risk protection, landowners may be less motivated to participate in carbon sequestration trading given the likelihood of carbon loss due to hurricanes and unfavorable liability rules, even though they recognize the potential of financial gains. Buying private insurance is gaining popularity as a tool (Cohen; de Figueiredo, Herzog and Reiner; Subak; Wong and Dutschke; Cairns and Lasserre) to mitigate the financial consequences for participating landowners from carbon loss. An investment company or a large forest company may be able to tolerate the losses from a forest fire or hurricane, but for a small forest owner with a valuable 30-year old plantation the financial losses may be difficult to overcome. There is a need, therefore, to document and analyze the impact of private insurance on a forest landowner’s portfolio of strategies, given the risk of carbon loss due to hurricanes.

Insuring against financial losses due to natural disasters such as hurricanes may help persuade landowners to participate in land management practices to sequester carbon. There are very few studies (Subak; Wong and Dutschke) that evaluate the role of insurance in creating the incentives for non-capped sources especially forest landowners to sequester and trade carbon in the face of various market and non-market risks and uncertainties that can lead to non-permanence.

The objectives of the thesis are to identify various sources of risk and uncertainty in greenhouse gas offset trading markets and to analyze the impact of these risks on agents' incentives to participate in these markets. Presence of risk and uncertainty might be a deterrent for both buyers and sellers of GHG offsets to participate in trading. This research is aimed at assessing the effect of risk of carbon loss due to natural disasters on forest landowners' incentive for purchasing land for new forest plantations for the purpose of creating carbon offsets and timber. This research also analyzes how insuring loss of carbon due to natural disasters might affect landowner incentives for creating and trading carbon offsets.

The remaining chapters in the thesis are organized as follows: Chapter II identifies various types and sources of risk and uncertainty associated with greenhouse gas trading markets; Chapter III assesses the impact of risk of carbon emissions due to hurricanes on landowner decision to participate in greenhouse gas trading markets; and Chapter IV analyses the effect of insuring carbon losses due to hurricanes on optimal landowner behavior. Finally, Chapter V presents the conclusions of this research.

Chapter II

SETTING UP A TRADABLE CARBON OFFSETS SYSTEM: RISK, UNCERTAINTY AND CAVEATS

Introduction

A vast and growing literature has emerged surrounding the feasibility and challenges of implementing a carbon offset program. A large number of concepts related to offset policy are currently being discussed in existing literature such as baseline, leakage, permanence, monitoring, verification, enforcement, financial feasibility, and third party verification. Cutting across these concepts is a vast array of risks and uncertainties. These risks play a major role in developing effective market designs that achieve aggregate emission caps while encouraging market participation and investment in carbon reduction activities.

However, carbon offsets will be traded only if they are generated and they will be generated only when the marginal costs of generating them are less than or equal to the marginal benefits. Marginal costs might include the costs of undertaking activities to sequester carbon, costs of participating in these markets which might require participants to register their reductions on greenhouse gas registries[6] and the costs from any unprecedented losses of carbon offsets due to market (regulatory changes) or non market (natural disasters) risks. Marginal benefits might include market and non-market

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[6] Examples of such registries are the California's Climate Action Registry (http://www.climateregistry.org/), the Northeast States for Coordinated Air Use Management (NESCAUM) Greenhouse Gas State Registry Collaborative (www.nescaum.org/Greenhouse/Registry/index.html) and Wisconsin's Voluntary Emission Reductions Registry (www.dnr.state.wi.us/org/aw/air/hot/climchgcom/index.htm).

benefits, such as the revenue from selling carbon offsets and the improvement in environmental quality, though landowners might not include non-market benefits in their cost-benefit calculations. The purpose of this chapter is to identify the sources of risk and uncertainty for GHG trading markets.

Defining Risk and Uncertainty

The distinction between risk and uncertainty is still a moot point for many. Frank H. Knight was one of the first ones to make a distinction between the two concepts. Knight elucidated, '*risk*' as to those circumstances under which the decision-maker can assign mathematical probabilities to the random states of nature, which she is faced with. Whereas, '*uncertainty*' as explained by Knight refers to circumstances when these random states of nature 'cannot' be expressed in terms of specific mathematical probabilities. However, the distinction made by Knight is not that clear because individual decision makers have unique perceptions of the uncertainty associated with the outcomes of any event. These perceptions can be expressed in terms of probability distributions, whether or not individuals make the decision based on past experience (which provides them with information regarding the likelihood of an outcome). "Decision makers must make probability judgments even with little or no empirical support" (Robison and Barry). We follow the distinction made by Robison and Barry: uncertain events are those, whose outcome is not known with surety, whereas, risky events are those uncertain events whose outcome has an impact on the individual decision maker's level of well being.

The distinction between uncertainty and risk will help to develop a sense of all possible risks that should be taken into account while setting up the carbon markets and all possible outcomes of the specific regulatory and contractual framework on which these markets are based. Risk as defined for this discussion is not the technical risk where in all possible outcomes are known beforehand (Knight), rather it is a general characterization of risk associated with all the decisions undertaken, a knowledge that not all outcomes can be characterized in advance (Faber, Manstetten and Proops).

Risk and Uncertainty in GHG Trading Markets

Risk and uncertainty are central to environmental decision-making. However, introduction of risk combined with the decision makers' risk attitude may alter the optimal decisions and optimal operation of a firm (Robison and Barry). This will be true for carbon permit trading markets as well when they come into force. Forestry-based carbon sequestration projects are also likely to face both market and non-market risks including the risk of carbon loss following natural disasters like hurricanes.

Carbon sequestration offsets like any other commodity can be bought and sold in the market place and as with any commodity trade, there are risks associated with carbon offset trading. The trade and investment outcomes, in terms of the amount of carbon sequestered and financial gains or losses of the stakeholders, of a GHG-sequestration project will significantly depend on how various risks and uncertainties are accounted for while designing these markets. The level of risk might have an effect on the price of carbon offsets and the costs of entering into such contracts which might affect the willingness of buyers and sellers to enter into the market. From a risk averse buyer's perspective, the more risk associated with a commodity, the lower the price they will be willing to pay. From a risk averse seller's perspective, the more risk associated with their participation in the market, the higher will be their required price. Risks in GHG-offset markets can arise at any juncture of a GHG-sequestration project, conception, development or implementation. Typically, these comprise risks associated with the planning, management and trade and transfer activities linked to the production of GHG-offsets[7] (Lynne and Kruse). The nature of the risks fall under three categories: institutional and policy, project risks and measurement risks.

Policy/Institutional Risks

Policy/institutional risks relate to baselines, monitoring/enforcement, and leakage.

Baseline Risk

Emission baselines are the best estimate of emissions that would occur in the absence of a project. Baseline estimates are necessary to calculate the net carbon reduction of a program or project. The baseline is the net carbon balance that would have occurred without the project or under a business-as-usual scenario. The difference between the baseline and the actual project carbon yield is the carbon offset or what may be claimed for carbon offsets (Wong and Mabee). In the case of LULUCF projects, the project developer must estimate what land-use activities would occur under business as usual, which GHG sources and sinks would be affected by these activities, and how and when these GHG sources and sinks would be affected. These factors can be a very

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[7] The terms offset and credit are used interchangeably where " the term credit is used to refer to a tradable unit that is based on undertaking activities that may not be taking place under an established cap" (King and Kuch, pp 6).

difficult to estimate because land uses are driven by multiple factors, including the availability of and demand for forest and agricultural resources, population growth, socioeconomic trends, government policies, cultural traditions, and natural disasters (Leining, Brown et al.).

Since there are no national standards for establishing baselines, the method of calculating baselines could change over time. If baselines become more relaxed, the carbon offsets generated by early adopters might be undermined. If baselines become stricter, the financial returns to sellers from program might decline. Baseline is a source of risk because the amount of carbon emissions occurring in the absence of the project could change over time due to changes in market incentives, technologies, or other government policies. For example, changes in tilling technologies could change carbon emissions from crop production that would occur in the absence of emissions control policies.

Two types of baselines have been considered in the literature: fixed and dynamic baselines. Fixed baselines are fixed for a project for the entire crediting lifetime, while dynamic baselines are allowed to be revised at certain time intervals. Fixed baseline might be simpler to estimate since it represents a form of guarantee that if the project is implemented as anticipated, it will generate the anticipated benefits. However, if the assumptions made in developing the reference scenario turn out to be unrealistic, then using a static emission baseline will produce an inaccurate estimate of project benefits (Leining). Sellers would bear the liability in case baselines are overestimated and buyers would bear the risk in case baselines are underestimated. Underestimated baseline might provide an incentive for sellers to enter the carbon trading market. Risk of overestimated baseline would be borne by the society as whole and might provide a disincentive for buyers to purchase carbon offsets. Dynamic baseline would evolve on the basis of a trend indicator based on past performance; however, past performance may not always reflect the rate of technological change/adoption or institutional changes in the future (Willems). Although using dynamic baseline might provide a more accurate way of estimating baselines, it raises the question of how frequently should the baseline be revised and whether the assumptions used at the time of initial estimation should be updated to reflect changes in institutional and market environment (Leining). Whether to adopt a fixed or dynamic baseline is a policy question and raises further uncertainty in baseline estimation. Depending on how the baseline is specified, this risk may be borne by the seller or buyer of the carbon emissions offsets. If fixed baselines are assumed for a forest plantation project and the actual sequestration is less than predicted sequestration, due to lack of appropriate management practices or loss of emissions due to unexpected events, the realized benefits of a carbon offset project will be less than expected and sellers will bear the baseline risk. If dynamic baseline is assumed for a forest plantation project, the revised baseline might be much higher, leading to creation of fewer carbon offsets, which might force the buyers to purchase more offsets from another source and reduce potential returns for sellers.

Monitoring Risk

Monitoring/enforcement risk is associated with the regulators' ability to detect whether the promised carbon sequestration activities are undertaken. If failure to comply with emissions controls is not detected, society loses the benefits of emissions controls. If failure is detected, the penalties for noncompliance may add to the original cost of controls, thereby increasing the risks for carbon offset sellers. Monitoring relates to the on-going measurement of carbon pools in with and without-project situations (Brown 1999). Monitoring without-project case may be a source of risk because of the need to monitor an area that is likely to undergo the types of land-use changes that would have occurred if the project had not been implemented. “Such changes in land use are hard to predict because of socio-economic, cultural, and political conditions” (Brown 1999).

There are no standard procedures for monitoring. Monitoring might include, remote sensing techniques, satellite and GIS imaging technology, low flying airplanes and on ground measurements etc. (Minott). Unavailability of standard procedures might be a source of risk for buyers, sellers and regulatory authority for detecting promised sequestration activities and ensuring compliance. Monitoring risk may be borne by buyers or sellers of carbon offsets depending on how liabilities for not controlling emissions are assigned. For example, utilities that purchase carbon offsets from farmers may be held liable if farmers fail to follow through with promised emission reduction activities. How liabilities are assigned and how activities are monitored will affect incentives to invest in carbon emissions reductions. Monitoring maybe a source of risk for buyers in case failure to create the promised carbon offsets goes undetected. Strict and accurate monitoring requirements might increase buyers’ incentives to purchase carbon offsets, while deterring sellers due to higher transactions costs and contractual obligations.

Leakage Risk

Leakage occurs when carbon sequestration at one site encourages increases in carbon emissions on some other site. Leakage is defined as unexpected GHG emissions when activities or markets are displaced. Leakage becomes a cause of risk when emissions are transferred to an uncapped source of emissions (Harkin and Bull). Landowners might clear or degrade forests on areas that are not part of a carbon sequestration project for harvesting timber or to use the land for agriculture. Limiting use of a forest plot for sequestration purposes potentially may reduce the supply of crops and tree products, and opportunities for formal or subsistence employment. This might encourage forest harvest on other sites or agricultural conversion activities in a different, uncapped land plot leading to leakage of GHG emissions out of another forest area (Chomitz). Failure to account for leakage might lead to overestimation of project benefits. Leakage risk is especially important because leakage can occur at regional, national or international levels, and thus can be very difficult to measure and predict (Leining).

Most of the literature concentrates on indirect leakage, where greenhouse gas emissions are encouraged elsewhere due to the market incentives created by the carbon emissions controls. For example, emissions controls, which increase fuel efficiency, may lower prices of fossil fuels leading to increased fuel consumption in regions, which are not under any obligation to reduce GHG emissions. “Production of energy intensive goods could shift to non Annex B countries due to lower costs of energy intensive products, as a result of carbon - sequestration” (Paltsev). Direct leakage may also occur when carbon emissions activities are simply shifted elsewhere within the firm or to other firms. For example, a farmer who plants trees to receive carbon offsets may clear trees elsewhere. Leakage is a source of risk to the society as society loses the benefits of emissions control. Also, depending on how liability for leakage is assigned at the beginning of a contract this risk may be borne by the sellers or buyers of the carbon offsets. This however is true only in the case of direct leakage, because in case of indirect leakage it might be difficult to trace back the cause of indirect leakage to any particular carbon sequestration project.

Murray, McCarl, and Lee estimate leakage from forest carbon sequestration programs and suggest that for small projects leakage may be small in absolute terms, but it tends to be larger in proportion to the direct project benefits than is the case for a larger program or policy. In the case of new forest plantation project, leakage would occur to the extent that the carbon sequestered in the new forest is offset by increased harvest and accompanying carbon losses on other forest lands outside of the plantation. Leakage also occurs from traditional forestland moving into agriculture (McCarl). If leakage goes undetected it would provide a higher incentive for sellers to enter carbon trading markets and a disincentive for buyers. High leakage rate from carbon offset projects might be a disincentive for sellers to purchase these offsets.

Project Risk

Project risk refers to non-performance of a carbon sequestration project in terms of not achieving the requisite target of carbon sequestration. On one hand carbon offset seller might not provide the promised quantity of offsets and on the other hand carbon offset buyer may not purchase the agreed quantity. Project risk includes physical risk and financial risk.

Physical Risk

Physical risks are associated with unexpected carbon emissions due to natural hazards or events such as fire, or hurricanes or changes in the rate of sequestration, which depend on weather and pests and might lead to non-permanence of stored carbon. Permanence is the ability of carbon to remain in a sink in perpetuity, or the ability of a forest carbon management proponent to guarantee an investor that the carbon on which a tradable offset is based will remain in the sink for at least the life of the project or purchase contract (Wong and Mabee). Land based carbon sequestration projects are subject to subsequent release through land use change, tillage change, harvesting, fires, or other natural and anthropogenic disturbances (McCarl, Murray and Schneider).

"Rapid loss of carbon could occur due to fires, droughts and changes in soil erosion rates associated with them" (Breshears and Allen). Demonstrating the permanence of benefits from land-use change and forestry projects is complicated by the continuous cycling of carbon between biomass, soils, and the atmosphere (Leining). Even though it can be argued that forests will re-grow following natural disasters, forest regeneration may not always occur, and if it does, the rate of carbon uptake from forest regeneration after such an event will tend to be much slower than the rate of carbon emissions from the event (Leining).

Non-permanence due to physical risk can have important implications in terms of project lifetime, insurance requirements or any other form of risk management. Even if project lifetime is pre-decided, the risk of premature emissions still remains (Subak). One way to account for non-permanence is to require that any lost carbon be replaced by purchasing replacement offsets. An important concern with this type of arrangement is that the project developer or other responsible party may not have the resources to replace the lost carbon. Moreover, the risk of defaulting on project commitments is greater with large losses and the risk increases with the possibility that offset value and, therefore, replacement costs will rise over time (Subak).

Physical risk is borne by the society due to loss in benefits of emission reduction, by the sellers of carbon offsets as they might lose the carbon offsets generated through sequestration and land management activities that they intended to sell, and by the buyers of carbon offset as they might lose the land based carbon offsets that they could have bought to meet their requirements under the Kyoto Protocol. Non-permanence of carbon offset projects would provide a disincentive for both buyer and sellers for trading, unless some form of risk management is adopted either by the buyers or sellers.

Financial Risk

Landowners will not participate in carbon sequestration programs if they expect to incur financial losses by participating. Financial risks are associated with reduced investment profitability due to changing economic factors such as changing output prices, interest rates, and currency values or project requirements. Two sources of financial risks are opportunity costs and transactions costs. Transactions costs are incurred in the process of searching for a trading partner, negotiating deals, securing regulatory approval, monitoring and enforcing deals and insuring against risk of failure. Changes in these requirements may change the costs of emissions controls and financial profitability of the project. In a formal carbon-trading regime, transactions costs would be a source of risk for the regulator if the regulator is responsible for bringing trading parties together and/or for monitoring and enforcing carbon contracts. Transactions costs will also be a source of risk for both sellers and buyers if they have to seek regulatory approval to participate in a particular contract and thus a disincentive for participation.

Opportunity cost is the income given up when land or other resources are committed to carbon sequestration activities. For example, the opportunity cost of land committed to carbon sequestration activities may rise due to changes in development pressures. The opportunity cost will vary spatially with land productivity, production choices and economic factors (Antle et al.). Higher opportunity cost of land for small landowners might lead to significantly higher cost of carbon sequestration for community plantations as compared to industrial plantation (Smith, J.). Financial risks continue to affect project performance even after expiration of the contract. For instance, once a sequestration project on a forestland terminates, the forest might be harvested or reverted to agricultural production causing release of stored carbon. Opportunity cost would become a source of risk to the sellers of carbon offsets, as they will have to divert resources towards generating carbon offsets. Lower opportunity costs for carbon offset projects would provide a higher incentive for sellers to enter carbon trading markets.

Measurement Risk

Measurement risk arises because it is difficult and costly to measure actual rates of carbon sequestered. In the case of LULUCF projects, the emission impacts of land management activities tend to be highly location specific and may vary drastically overtime (Leining). "A major constraint to successful forestry-based carbon offset programs is the lack of reliable, accurate and cost-effective methods for monitoring carbon storage" (MacDicken). If it is not possible to measure the greenhouse gas benefits from LULUCF projects with the same degree of certainty as the benefits from projects in other sectors such as electric utilities or renewable energy, then LULUCF project might not provide the similar benefits and/or incentives to emission reductions from projects in other sectors (Leining). Spatial and temporal heterogeneity of carbon present in agricultural and forest production systems tends to increase the difficulty and expenditure of estimating the amount of carbon present. Moreover, carbon sequestration usually occurs slowly with wide fluctuations due to changes in weather and/or natural pest pressures.

Measurement uncertainty is due to limited data availability, and limited resources available to capture this data (Harkin and Bull). While some data are available for average carbon stock densities for different forest types, regions, and land-use activities, the actual carbon stocks can be highly variable by site, and even average data may be lacking for some regions and land-use activities (Leining). Moreover, the data available for measuring above ground biomass for specific tree species and geographic regions is not easily and freely available (Brown, 2002). Measurement uncertainty can stem from various sources: uncertainty due to using average and/or approximate values, uncertainty of science of forest carbon capture, uncertainty in measurement of parameters that cannot be measured directly such as diameter and height of trees, and finally the uncertainty stemming from systematic biases, mistakes and unintentional errors during forest inventory (Harkin and Bull).

Measurement risk also stems from the techniques of sampling, measurement instruments, models and regression errors. Where it is not possible to do frequent inventories either due to high costs or inaccessibility of region, remote sensing techniques or models can be used to estimate carbon fluxes and stocks. The risk is associated with the fact that model outputs are difficult to verify with actual data. Satellite remote sensing can be used in conjunction with on-site measurement to monitor absolute changes in land-cover type by area over time, but it currently is not a substitute for on-site measurement of biomass stocking densities and biomass condition (Leining).

There is a tradeoff between measurement risk and costs. By spending more on improving measurement techniques the risk of measurement can be lowered. The more extensive and more frequent the carbon stock inventory that is required, the better the estimates of stock changes and the higher the cost of the project (Leining). Error in measurement is a source of risk to the society if the actual rate/amount of sequestration is less than the measured level of sequestration. It will also be a source of risk to sellers because the carbon offsets bought by them would not be equivalent to the actual (lesser) amount of carbon sequestered. New and improved technologies for carbon measurements in forests might provide additional security in carbon offset trading to both buyers and sellers and facilitate the optimal design, deployment, and management of forest and wood product systems that will provide additional carbon sequestered and ancillary benefits. Inaccurate measurements would provide a disincentive for both buyers and sellers as it will not be possible to precisely define and measure the commodity being traded.

Impact of Risk and Uncertainty on the Supply and Demand for Carbon Offsets

The perfectly competitive market environment is based on the assumption that buyers and sellers have full knowledge of the prevailing market conditions in the current period and as well as in all future periods. Individual decision makers thus know the outcome of their choices with certainty. Moreover, information is accessible by everyone at no cost. These assumptions rule out any uncertainty about future market developments. However, individuals are faced with uncertainty in most decisions that they make in real life. "Uncertainty is a fact of life" (Varian, p. 212).

Source of uncertainty is lack of information; however availability of information also does not imply conformity with real world conditions. To illustrate, a forest planter might believe, based on her experience and information that the baseline for on-site GHG emissions is '*x*' tons/acre of land. From her point of view there is no uncertainty. But, the regulatory authority still might change the baseline and this experience in turn, will change the planter's expectations about the baseline.

"Risk may be viewed as resulting in an additional cost" (Robison and Barry). These costs must be incorporated in the optimal decision making process of the consumers, firms and the society. The consumers will undertake a risky activity, like buying carbon offsets, only when they are compensated for the decline in their utility level. The firms will undertake risky activities only if they are compensated for certain costs and the society will do so, only if it is compensated for a decline in its welfare (King and Kuch). “Risk preferences of agents and regulatory agencies play a significant role in determining the participation in carbon - sequestration projects” (Woodward).

Concluding Remarks

Uncertainty and risk are central to environmental management problems. Given the various sources of risks and uncertainty associated with carbon offset trading markets identified in this paper there is need to assess the impact of these risks at the time of markets establishment and/or project development for such. These risks might affect buyers and sellers alike and may have an impact on their decision to participate in GHG trading markets. Some form of risk mitigation strategy might be necessary to improve incentives for landowner participation. Policy and institutional mechanisms to manage risks may be an important component of GHG trading programs.

Chapter III

INCENTIVES FOR A FOREST LANDOWNER TO SEQUESTER AND TRADE CARBON UNDER UNCERTAINTY: IMPACT OF HURRICANES IN SOUTHEASTERN UNITED STATES

The carbon in agricultural and forestry projects is stored in woody vegetation and soils; and there always exists the possibility that it might be lost, either through deliberate management measures or because of natural events such as hurricanes or wildfires (Sampson and Sedjo). Though few, if any, things in nature are truly permanent, it can be argued that these projects buy important time for developing alternate technologies that reduce fossil fuel usage. Therefore there is a need for properly calculating the value of carbon sequestered over time, as well as planning and protecting against premature losses of carbon. As the probability of national and international carbon markets increases, it is important to look at the impact of uncertain weather conditions on market trading outcomes. "No matter how well every person performs under a carbon offset agreement, there are always disasters that can overwhelm the best efforts. Floods, fires, insect and disease epidemics, and similar things can set back or destroy the best land management system." (Sampson, p. 5).

Hurricanes and Forest Carbon

Given the change in global climate that may be occurring, the probability of increased exposure to natural hazards, especially hurricanes along the east coast of U.S. may be increasing (Smith, E.; Gray; Knutson et al.; Knutson and Tuleya). Future growth rates of forests may be increasingly uncertain due to the possibly growing probability of more frequent and intense natural disturbances such as hurricanes (Knutson, Tuleya and Kurihara), tornadoes, wild fires and insect or disease epidemics, which can convert much of the biomass back to CO_2. Estimates of forest carbon sequestration do not usually analyze the impact of hurricanes on forest carbon stocks (McNulty). The majority of Atlantic hurricanes making landfall hit the U.S. east coast, more than 55% of which is covered by forests (USDA Forest Service). Hurricanes lead to direct damage to a standing forest in terms of wood that has been downed, increase in rotting dead wood, which acts as a fuel for wild fires, and increased risk of insect infestations following a storm. Such damage results in an increase in carbon emissions over the years following the storm. "A single hurricane can convert 10% of the total annual carbon storage for the U.S. forests into dead and downed forest biomass" (McNulty, p. S17).

Risk averse landowners will undertake risky carbon production activity only if they are compensated for the costs associated with hurricane risk as well as the cost of producing carbon offsets (Robison and Barry). A hurricane would increase the landowner's costs in four ways. Firstly, it will reduce the number of offsets sold in the market and consequently the stream of net returns. Secondly, it may lead to some form of penalty on the landowner. Thirdly, it may lead to an increase in investment in one or more pre/post-hurricane risk mitigation strategies and fourthly, it might lead to decline in future timber returns. Pre-hurricane risk mitigation strategies could include 1) planting species that are less prone to breakage due to hurricanes (McNulty); 2) choosing locations of projects to minimize exposure to hurricanes (Brown, November 2002); 3) purchasing insurance (Brown, November 2002); and 4) self insurance with a buffer of unsold carbon offsets (Brown, November 2002). Post-hurricane strategies could include 1) salvaging downed wood and helping the landowners to market this downed wood; and 2) undertaking fire management to reduce fire risk after hurricanes (McNulty). Combination of all or some of these strategies represents the landowners' "portfolio of strategies" to manage hurricane risk.

Joint Production and Catastrophe Risk Models in Forestry

Existing forestry literature on natural disasters deals with analyzing the impact of catastrophes on the optimal rotation age, optimal management strategies and optimal net present value of returns. Reed analyzes how optimal rotation and expected land value are affected by natural catastrophes, in particular fire. Reed shows that expected value of returns can be determined with a simple modification of the Faustmann formula. For the case of fire risk, Reed assumes that fires occur in a time-independent Poisson process and result in total destruction, and he extends the formulas to include salvagable yield following fire and fire risk that depends on stand age (Haight et al.). However he does not consider the problem in a setting where the landowner has the opportunity to earn revenue from carbon offset trading. Haight et al. consider economics of loblolly pine plantations under risk of hurricane damage. They apply the assumptions about stochastic fire damage to the case of hurricane damage, and use Reed's formulas to estimate the effect of the risk of hurricane damage on the economics of loblolly pine plantation management. Both of these papers assume a fixed percentage of hurricane damage for a single stand management model. Goodnow Jr. examines the effect of ice damage on loblolly pine plantations to determine if management decisions can minimize net present value losses. He used a decision tree framework to show that in most instances changing management plans could not minimize losses and altering management plans could result in suboptimal net present value if no ice storms occur. There is no assumption about non-timber value of forests especially from carbon sequestration and carbon-offset trading. These papers do not deal with decisions made by risk averse decision makers. Koskela and Ollikainen consider the impact of multiplicative and additive risk in forest growth and forest stocks on harvesting in a two-period non-expected utility model. These models assume normality for biological risks and no actual data are used.

In this study we use a multi-stand model with stands in different regions. Our model analyses the impact of hurricane risks, which are correlated across regions. The model assesses the impact of hurricane risk on returns from joint production of timber and carbon offsets using a stochastic simulation model to account for hurricane losses over the lifetime of a project. Our framework is a step towards analyzing how risk management strategies can increase landowners' incentives to participate in carbon markets. We consider the pre-hurricane risk mitigation strategy of choosing different locations for carbon-sequestration, which are also managed for timber sales. Different regions have different probabilities of being hit by hurricanes and different sequestration rates. The model evaluates landowner behavior in terms of the portfolio of land investment strategies, which would allow trade-off between planting in locations with higher exposure to hurricanes but higher rate of sequestration or in locations with lower exposure to hurricanes and lower rates of sequestration. The analysis is limited to new forest plantation projects that are undertaken to manage the forest stand for both carbon sequestration and carbon offset-trading and timber sales.

Objectives

The main objective of this chapter is to provide a comprehensive economic assessment of choosing project locations to manage risk for landowners engaged in GHG mitigation and trade in the forestry sector in hurricane prone regions of United States. Research objectives are to:

1. Develop a conceptual model to analyze a forest landowner's/investor's "portfolio of location choice strategies" given the risk of carbon loss from hurricanes in the eastern United States and varying levels of landowner risk aversion.
2. Estimate the empirical model of the forest landowner to illustrate the impact of hurricane risk and landowners' risk aversion on the landowners' "portfolio of location choice strategies".

Model

It is assumed that the landowner acquires land for producing carbon offsets and timber from new plantations. Another assumption is that forest use of the land for timber and carbon sequestration purposes is the best use in perpetuity. Moreover, the landowner invests in forest land only with the motive of market returns and does not value non-market returns of land such as improved environmental quality.

The focus is on the state of South Carolina because this is the only state for which a post-hurricane forest inventory is available from USDA’s Forest Inventory Analysis[8] (FIA). The forest inventory was carried out following hurricane HUGO which hit South Carolina in September 1989. The FIA was carried out between February 1990 and June 1990. U.S. Department of Agriculture (USDA), Natural Resources Conservation Service (NRCS) data on major land resource areas (MLRA) of the conterminous United States are used to divide the study area into three major sub-regions – coastal, piedmont and upland (Figure 1).

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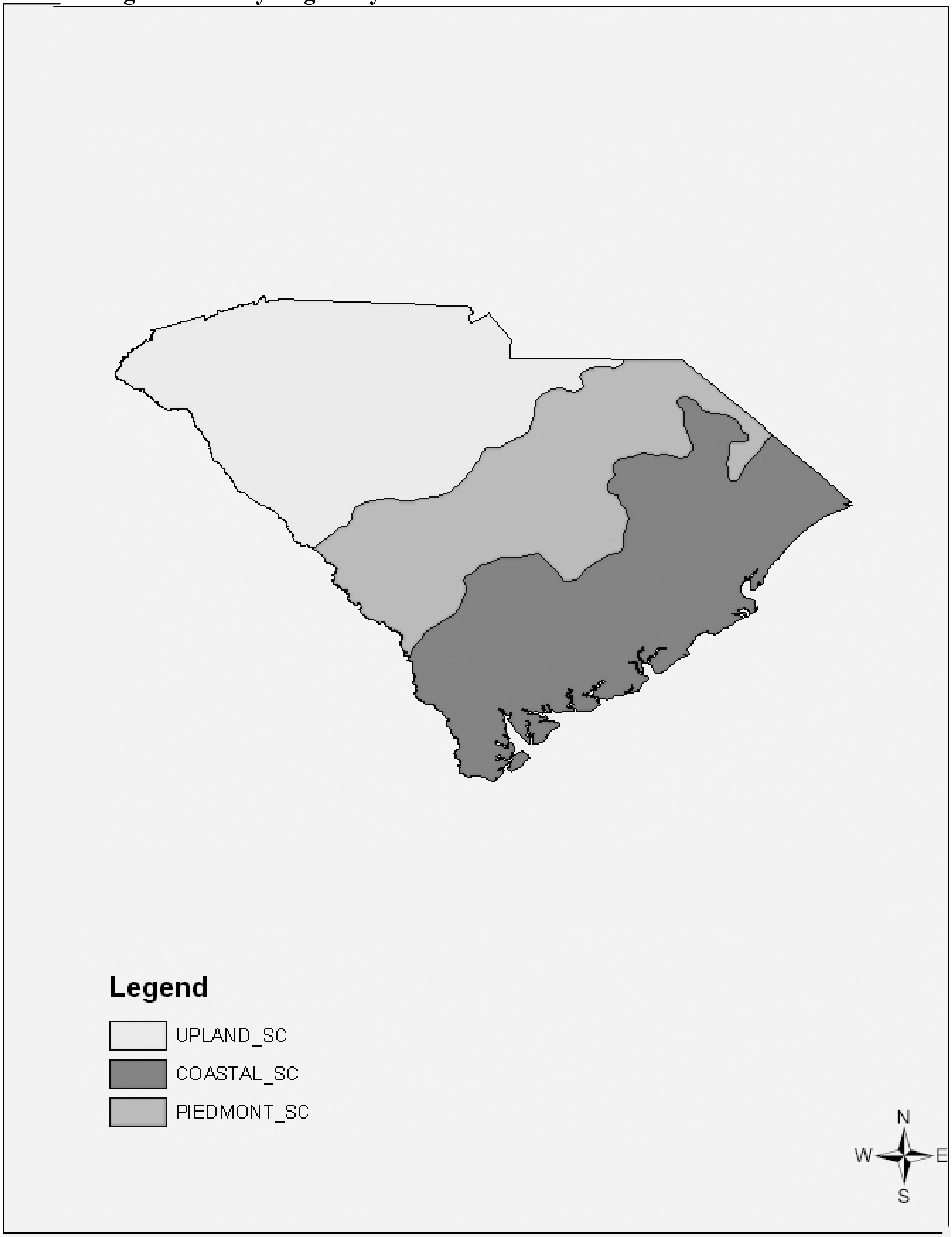
[8] http://www.fia.fs.fed.us/

Figure 1: Study Region by Land Resource Areas – South Carolina



Accounting and Liability Scenarios

Many accounting and liability scenarios have been proposed to take account of non-permanence of forestry based carbon offsets. Under the Kyoto Protocol, non-permanence is an accounting problem only in non-Annex 1[9] countries (Pedroni and Locatelli). If an Annex-B[10] forest is burned or harvested, the resulting CO_2 emissions are debited on the national GHG account of that country. Under such a scenario, liability would lie with the seller so long as a carbon sequestration contract is in place but would revert to the buyer/renter of offsets when the rental contract expired (Sedjo et al.). This system is an evidence of mixed liability rules which is gaining interest of researchers. In this context private insurance might have a major role to play in terms of covering the damages, in case the seller or the buyer defaults.

One approach which is used both as a liability rule and an accounting rule is the ton-year accounting where carbon sequestration is valued on the basis of both the number of tons sequestered and years over which it is sequestered (Noble et al.; Herzog, et al). Under this approach the project/seller is responsible for proportional liability (IPCC). A ton-year equivalency factor can be used to determine the relative climate effect of carbon emissions and removals over time and the corresponding liability of the project

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[9] Countries not included in Annex I of the United Nations Framework Convention on Climate Change UNFCCC. Non-Annex I countries do not currently have binding emission reduction targets. (http://www.co2e.com/common/glossary.asp#N)

[10] Annex B countries are the 39 emissions-capped industrialized countries and economies in transition listed in Annex B of the Kyoto Protocol. Legally-binding emission reduction obligations for Annex B countries range from an 8% decrease (e.g., various European nations) to a 10% increase (Iceland) in relation to 1990 levels during the first commitment period from 2008 to 2012. (http://www.co2e.com/common/glossary.asp#N)

implementer (IPCC). For a given pattern, the equivalency factor will be a function of the time horizon and discount rate selected.

One major drawback of the ton-year approach is the debate over how to establish the equivalency factor, which cannot be determined uniquely and is mostly a policy decision rather than a scientific one (Marland et al., Brown November 2002). The determination of an equivalency factor gives rise to a basic policy question that must be answered for any such system; which is how long carbon must be sequestered to be considered equivalent to "permanent" emission avoidance. Other criticisms of this approach are that offsets are created very slowly under this approach, which might discourage short term projects and also there is a lack of symmetry between the assigned offsets and “debits” in case of emissions (Marland et al.).

Another approach is to define ‘Temporary Certified Emission Reductions’, which are only valid over the lifetime of a project or a forest plantation and expire thereafter. The activity host or the seller of the offset is liable for any loss of carbon during the contract period and the buyer of a temporary offset has to bear the liability of finding a follow-on offset (Chomitz and Lecocq).

The third approach is to account for the average carbon that can be stored under a certain project or a given forest plantation, such that the stochastic carbon stocks are averaged over a predefined period of time, which could be the project’s lifetime or the ending date of a contractual agreement. It is unclear who will bear the liability of unexpected losses in sequestered carbon under this approach. A fourth approach is to consider the carbon offsets to be permanent or the ‘stock change’ approach (Schlamadinger et al.) where any emissions are deducted from the emission reductions.

A fifth approach has been suggested by Marland et al. under which emission offsets can be rented on a yearly basis. A rental contract for emissions offsets will help to establish continuous responsibility for sequestered carbon by providing a financial incentive to sequester carbon on an annual basis and offsets would be assigned when carbon is sequestered and debits would accrue when carbon is emitted. This system would be based on renewal of rental agreements. The various accounting approaches and liability rules can be used in different combinations.

Two different accounting and liability mechanisms or carbon payment schemes are considered for this research: 1) Stock Change method with Proportional landowner Liability (SCPL), and 2) Rental Approach with Full landowner Liability (RAFL). The stock change approach for accounting for any changes in carbon stocks has been approved under the Kyoto Protocol for Land Use, Land Use Change and Forestry projects for Annex 1 countries (Schlamadinger et al.). Under the stock change approach it is assumed that the landowner will receive a one-time payment for carbon offsets when sequestration takes place. The offsets purchased with this payment are valid until the end of the contract period, which is pre-determined and equal to the rotation age in each region. It is assumed that the landowner is able to sell all the offsets that are created every year and receives a payment for ‘carbon-years’, which is equal to volume of carbon times price of carbon times the number of years those offsets are expected to remain sequestered. In this case, the liability lies with the seller for maintaining carbon offsets while the contract is in place. Also proportional liability is assumed which implies that if the stored carbon is released during the contract period, the landowner should be debited an amount of offsets proportional to the difference between the predetermined contract duration and the actual project duration (the ‘period of non-compliance’) (Brown, November 2002). Once the rotation age is reached, the forest is harvested unless it is cleared because of extensive damage caused by hurricanes(s) prior to reaching the rotation age in each of the regions, in which case the landowner faces proportional liability.

The second approach that is considered is the rental approach suggested by Marland et al., which prescribes that carbon offsets are rented on a periodic basis instead of being sold. This system provides full credit at the time of sequestration in return for full liability if the sequestered carbon is later released. Debits and credits are accounted on an annual basis and are counted in the time interval that the loss or gain of carbon occurred. Under this system the liability resides with the activity host or the landowner so long as a rental contract is in place but reverts to the buyer/renter of offsets when the rental contract expires (in one year). With the proposed carbon rental system, commitments are made one contract period at a time. The credits and debits are symmetric and instantaneous. Under this approach it is assumed that the landowner is able to rent all the offsets that are created every year. At the end of the rental agreement the buyer/renter incurs an emissions debit and is liable to either renew the carbon rental contract for another year or to find another way of meeting her emissions reduction obligations, and the host is released from further liability. If the carbon remains sequestered, the host/landowner could (a) renew the lease, at the same or newly re-negotiated terms, (b) lease the offset to another buyer/renter, (c) retain the offset for his/her own use, or (d) set free the sequestered carbon if they had a higher use for the committed land such as harvesting the forest plantation for timber sale. This approach does not specify a date for expiration of carbon offsets. When expiration occurs, the rental payments cease.

A simple numerical example will clarify the difference between the two approaches. Suppose the landowner sequesters 10 tons of carbon in time period 1. The sequestration project is assumed to be valid for a period of 10 years (contract period). Under the SCPL approach the landowner receives a one time payment equal to volume of carbon times price per ton of carbon ($10) times the number of years the carbon is expected to be sequestered (10 years) times the discount factor, since the payment is received at the end of the first year (= 10 x 10 x 10 x discount factor). For simplicity assume that carbon is sequestered only in the first year and expected to remain sequestered for a total of ten years. Suppose a hurricane strikes in year five and five tons of carbon are lost. In case of proportional liability the landowner will be required to return whatever they received for the five tons time the proportion of years it does not remain sequestered times the discount factor (= 5 x 10 x 10 x 5/10 x discount factor). The net present value of returns from sequestering under the SCPL approach is $756 (Table 1).

Table 1: NPV for different accounting and liability schemes: A simple illustration

Age	Discount factor (Interest rate = 6%)	SCPL	RAFL
1	0.94	943.396	94.339
2	0.89	0	88.999
3	0.84	0	83.961
4	0.79	0	79.209
5	0.75	-186.814	37.362
6	0.70	0	35.248
7	0.67	0	33.252
8	0.63	0	31.370
9	0.59	0	29.594
10	0.56	0	27.919
NPV		**756.581**	**541.25**

Under the RAFL scenario, the landowner receives a payment for sequestering 10 tons of carbon in the first year. The contract for sequestering these 10 tons in the second year and the years following has to be renewed annually. Thus each year the land owner receives volume of carbon times price of carbon ($10.00) times the discount factor (= 10 x 10 x discount factor). Suppose in year five a hurricane destroys five tons of carbon and from year 5 onwards the landowner has only 5 tons to rent in each of the following years (= 5 x 10 x discount factor). In this case the landowner does not have to return anything they received in the past for sequestering carbon because the contract is renewed annually. Landowners will just have those many less carbon offsets to rent. The net present value of returns from sequestering under the RAFL approach is $541.

This simple example however does not include any returns from harvesting. We may also expect the net present values to be lower in case the landowner is held liable for loss of carbon offsets when a forest is harvested at the rotation age under both approaches.

The problem of the landowner under both the SCPL and RAFL approaches is to choose the optimal amount of land acquired in each of the regions, A_i (i= 1, 2, 3), at the beginning of the project period, i.e., at t =1, for the purpose of creating carbon offsets and selling timber so as to maximize expected utility.

Forest Biomass Yield

The following timber yield function is used (Chang; Amacher et al.):

$$G_{it}(t, SI, w) = e^{9.75 - \frac{34.01}{t^2} - \frac{3418.10}{tw} - \frac{740.82}{tSI} - \frac{1527.66}{SI^2}} \qquad \ldots (1)$$

t refers to stand age, w refers to planting density and SI refers to the site index. Biomass is converted into carbon using a carbon conversion constant, c, and the carbon conversion equation for SCPL and RAFL is as follows:

$$R_{it} = c(G_{it} - G_{it-1}) \qquad \ldots (2)$$

where, R_{it} represents the incremental volume of carbon offsets created in the current period and G_{it} is the biomass volume per acre.

Hurricane Landfall Probability

Hurricane landfall occurrence is assumed to follow a Poisson distribution in all three regions (Parisi and Lund; Haight et al.; Jagger et al.). The Poisson distribution is used to model the average number of random occurrences per interval:

$$P(m) = \frac{e^{-\pi_{it}} \pi_{it}{}^{m}}{m!}\text{; E }(m) = \pi_{it}\text{; Var }(m) = \pi_{it} \qquad \ldots (3)$$

where, *P(m)* is the probability of m hurricanes, π_{it} is the average rate of hurricane arrival and $0 \leq m < +\infty$.

Hurricane Damage

The volume of carbon offsets per acre created in past periods plus the new offsets created in the current period available for renting over the remainder of the project period, B_{it}, under the RAFL is defined as follows:

$$B_{it} = R_{it} + B_{it-1}, B_{i0} = 0 \qquad \ldots (4)$$

The volume of offsets lost per acre, M_{it}, due to hurricanes in all past periods since the trees were planted plus the offsets lost in the current period under the RAFL is defined as follows:

$$M_{it} = D_{it} + M_{it-1} \qquad \ldots (5)$$

The cumulative quantity of carbon offsets lost per acre, D_{it}, from m hurricanes in a given year t under both SCPL and RAFL is defined as follows:

$$D_{it} = \sum_{j=1}^{m} D_{itj} \qquad \ldots (6)$$

When the age of forest stand is less than merchantable age, $t \leq a_i$, or when the cumulative damage from m hurricanes is less than 20% and the age of forest stand is greater than the merchantable age, i.e. $t \geq a_i$, then marginal damage from the j^{th} hurricane is given by:

$$D_{itj} = \overset{j}{d}_{it}\left(\sum_{t} R_{it} - \sum_{w=1}^{j-1} D_{itw}\right), \text{ where } j \equiv \text{w} = 1, 2, 3 \ldots m \qquad \ldots (7)$$

The proportion of marginal damage to accumulated carbon due to the j^{th} hurricane is represented by the term $\overset{j}{d}_{it}$ and is same as the proportion of forest stand that is downed biomass.

If the cumulative damage from *m* hurricanes in a given year exceeds 20% and the age of the forest is greater than the merchantable age, i.e. $t \geq a_i$, then salvage occurs and the damage is reduced and is defined as follows:

$$D_{itj} = \overset{j}{d}_{it}\left(\varepsilon_{1t}\left(1-ke_1\right)+\varepsilon_{2t}\left(1-ke_2\right)\right)\left(\sum_{t} R_{it} - \sum_{w=1}^{j-1} D_{itw}\right) \qquad \ldots (8)$$

$0 \leq \overset{j}{d}_{it} \leq 1$; $0 \leq e_1 \leq 1$; $0 \leq e_2 \leq 1$; $0 \leq \varepsilon_{1t} \leq 1$; $0 \leq \varepsilon_{2t} \leq 1$; $j \equiv w = 1, 2, 3 \ldots m$

The growth in forest biomass in the following period is assumed to be the same as what would occur without hurricane damage. The proportion of marginal damage $\overset{j}{d}_{it}$ from the j^{th} hurricane in a given year is generated randomly from a distribution estimated for each region. The coefficients ε_{1t} and ε_{2t} represent the average proportions of timber and pulpwood, respectively, by age. The coefficient *k* represents the proportion of downed forest biomass (timber) that is salvaged and converted into wood products. The terms e_1 and e_2 represent the proportion of the carbon content that was prevented from being emitted due to conversion of timber and pulpwood into wood products after salvage of part of the downed wood following a hurricane.

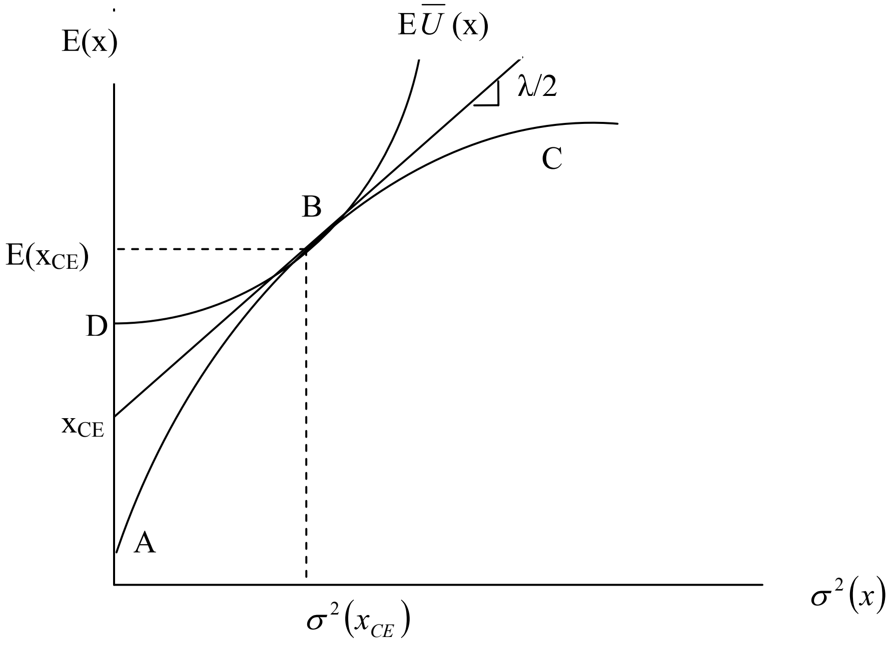
Basic Optimization

An individual landowner must be willing to take on greater risk to obtain greater expected returns from sequestering and trading carbon offsets and selling timber in the face of risk of carbon loss and timber damage from hurricanes. The landowner has the choice of purchasing land in three different regions, which are incongruent in terms of hurricane strike probabilities and carbon sequestration rates. The constraint facing the landowner is the amount of initial wealth available for investing in land. Thus the landowner has a portfolio management problem given the likelihood of risk of carbon loss and timber damage during the lifetime of carbon sequestration project.

Markowitz proposed a mean-variance (EV) approach to select efficient asset portfolios. Mean variance analysis assumes that the agent's preferences or utility can be expressed in terms of only the mean and the variance of returns from risky assets (Levy and Markowitz). Given an agent's preferred level of risk, a particular portfolio can be constructed that maximizes expected return for that level of risk. The main advantages of mean variance approach to portfolio selection are computational simplicity (Zhao and Ziemba) and good intuitive explanation of the advantage of asset diversification (Zhao and Ziemba). The main criticisms of E-V approach is the static nature of analysis that requires agents to take decisions only at the beginning of the planning horizon (Zhao and Ziemba) and the fact that risk is measured by a single number, the variance of returns (Steinbach). The justification for mean variance analysis has included one or more of the following: expected returns are normally distributed; preferences of decision makers can be represented by quadratic utility function; and expected returns satisfy the location and scale condition (Meyer; Robison and Barry). These conditions are sufficient but not necessary. For the mean-variance model to yield solutions consistent with expected utility maximization, existence or non-existence of some of these conditions may be tested using statistical procedures.

Similar to the approach suggested in Robison and Barry, the current model is restricted to linear combinations of random variables. In case of Robison and Barry's model this implies that landowner's choices can be approximated by a mean-variance efficient set that is comprised of a risky asset and a risk-less asset. Our model consists of linear combinations of several risky variables, the allocation of land in 3 regions. However, the figure adopted from Robison and Barry provides a simpler illustration of the linear approximation. In this setting the optimal portfolio choice from the E-V efficient set can be obtained by maximizing a linear approximation of the E-V frontier as shown in Figure 2. This linear approximation of the E-V frontier is tangent to the E-V set at the point where the slope of the tangent is given by $\lambda/2$, where λ is the landowner's coefficient of risk aversion. The optimal portfolio in the E-V space is determined by the tangency of the E-V frontier and the iso-expected utility curve $E\overline{U}(x)$, which is represented by point B. In order to develop this approach mathematically, we can extend the linear tangent so that it cuts the axis at x_{CE}. Since x_{CE} is a risk-less return with zero variance, it can be considered as the 'certain' return that yields the same expected utility as a risky asset with expected return $E(x_{CE})$ and is called the 'certainty equivalent' of risky assets.

Figure 2: Optimal Portfolio in the Mean-Variance Space



Source: Robison and Barry

Certainty equivalent of a risky investment is the certain or risk free return which yields the same utility as the risky investment. The point, $x_{CE,}$ gives the same satisfaction as the chosen combination of risky and risk-free assets at B. There is a difference between D, the "true" certainty equivalent which is the intersection of the $E\overline{U}(x)$ isoquant with the vertical axis, and x_{CE}. The discrepancy occurs because the straight line is only a local approximation to the indifference curve at B. The risk premium is defined as $\pi = E(x_{CE}) - x_{CE}$. Let us consider the equation of a straight line in the Figure 2 and by definition of slope and intercept, equation of a line through a point $E(x_{CE})$ is given by:

$$E(x_{CE}) = x_{CE} + \frac{\lambda}{2} \times (\sigma^2_{X_{CE}}) \qquad \ldots (9)$$

$$\pi = \frac{\lambda}{2} \times (\sigma^2_{X_{CE}})$$

λ is the Arrow-Pratt coefficient of absolute risk aversions (-U"/U'). λ is defined as follows:

$$\lambda = \frac{-U''(x)}{U'(x)} \qquad \ldots (10)$$

where, $\sigma^2(x)$ is the variance of returns, and $\frac{\lambda}{2}\sigma^2(x)$ is an expression for risk premium derived by Pratt (Pratt; Robison and Barry). Arrow-Pratt coefficient, λ, is positive if the landowner is a risk averter, zero if the landowner is risk neutral and negative if the landowner is a risk seeker. Different Pratt coefficients will give different optimal solutions and will also allow us to examine the risk – return trade-off for differing levels of absolute risk aversion. The higher the level of risk aversion the higher the risk premium of a risky investment.

In the mean-variance space, maximization of expected utility is equivalent to maximizing the certainty equivalent of risky returns. Mathematically the choice of optimal portfolio in the mean variance space is equivalent to maximizing the certainty equivalent of risky returns such that slope of the certainty equivalent line equals the equilibrium slope at the tangency of the $E\overline{U}(x)$ curve and the E-V set, which has been assigned a slope of λ/2 (Robison and Barry). In this case the objective is to maximize the certainty equivalent (CE) of net present value of net returns x:

$$\underset{A_i}{Max} \text{ CE (x)} = \text{E(x)} - \frac{\lambda}{2}\sigma^2(x) \qquad \ldots (11)$$

Subject to: $$x = \sum_{i=1}^{n} Q_i \qquad \ldots (12)$$

where, x refers to sum of the net present value of returns from carbon offsets and timber in all regions. Q_i is the net present value of returns from carbon and timber from all rotations over the planning horizon T in region i, and n is the total number of regions.

Land purchase costs are not deducted in calculating the net present value of returns. The expected net present value is used to estimate the land price in determining the portfolio of land investment holdings. The model is solved separately under the two carbon payment scenarios, SCPL and RAFL. Net present value of returns from the project lifetime, Q_i, is defined as follows for the SCPL:

$$Q_i = \left(\sum_{t=1}^{T} \frac{\left(pR_{it}(T-(t-1)) - py_{it}\, D_{it}\left(T-t\right) + qy_{it}\, K_{it} - Z \right)}{(1+r)^t} + \eta_i \frac{qJ_{iV_i}}{(1+r)^{V_i}} - \sum_{i=1}^{n} C_i \right) A_i \quad \ldots (13)$$

The landowner sells an estimated quantity of incremental carbon offsets, R_{it}, per acre in a given year t for price p, which is assumed to be constant over the lifetime of the project, thus real prices are assumed. T is the terminal time period (assumed to be 100 years), D_{it} is the cumulative quantity of carbon offsets lost per acre from m hurricanes in a given year t, m represents the total number of hurricanes in the current period, y_{it} is a binary random variable which takes on value 1 when there are one or more hurricanes in given period and value 0 in years with no hurricanes.

Z represents the annual costs of stand maintenance as well as costs incurred following harvest or hurricane damage and is defined as follows:

$$Z = H_i + y_{it} S_i + y_{it} F_i + y_{it} N_i \qquad \ldots (14)$$

H_i[11] is the base monitoring and verification cost per year per acre and is incurred in both hurricane and non-hurricane years. N_i is the cost of monitoring and verification per acre in hurricane years, which is in addition to base monitoring cost. F_i is the site preparation and replanting cost per acre and is incurred in years following normal harvest or hurricanes, which might result in the stand being harvested or destroyed at younger ages when the biomass is not merchantable. S_i is the cost of pre-commercial thinning per acre of land and is incurred when a hurricanes leads to partial destruction (between 20%-40%) of the forest stand (Stephen Prisley, Associate Professor, Department of Forestry, Virginia Tech). η_i is the total number of normal harvests in region *i*. The timber is assumed to be sold at a price *q*, which is assumed to decline in hurricane years and return to pre-hurricane level in the following year (please refer to the empirical model). C_i represents the stand establishment cost per acre incurred at the initial time and *r* is the risk-free rate of time preference (assumed to be 5%). J_{iV_i} , the volume of timber available for sale per acre after V_i (which is the rotation age in region *i*) years have elapsed since the forest was planted initially or replanted following a hurricane. A_i

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[11] This also includes an annual property tax of $1.25/acre, which is the average for South Carolina (http://www.dnr.state.sc.us/wild/forlegacy/forlegacy.html)

represents the amount of land investment in the three regions. The rotation age, V_i, and A_i are choice variables for the landowner.

Net present value of returns from the project lifetime, Q_i, is defined as follows for the RAFL:

$$Q_i = \left(\sum_{t=1}^{T} \frac{\left(pB_{it} - py_{it}M_{it} + qy_{it}\, K_{it} - Z \right)}{(1+r)^t} + \eta_i \frac{qJ_{iV_i}}{(1+r)^{V_i}} - \sum_{i=1}^{n} C_i \right) A_i \qquad \text{… (15)}$$

Under the RAFL approach B_{it} represents the volume of carbon offsets per acre created in past periods plus the new offsets created in the current period available for renting over the remainder of the project period. M_{it} is the cumulative loss of carbon offsets per acre from hurricanes over all past periods and is subtracted from the cumulative carbon offsets, B_{it}, which are available for sale in each period.

Timber Harvest and Salvage

J_{iV_i}, the volume of timber available for sale per acre after V_i (which is the rotation age in region *i*) years have elapsed since the forest was planted initially or replanted following a hurricane is defined as follows:

$$J_{iV_i} = G_{it} - \sum_{t} y_{it} O_{it}\text{, where } O_{it} = \overset{j}{d}_{it}\, G_{it} \qquad \text{… (16)}$$

O_{it} is the timber loss due to hurricanes in period *t*. J_{iVi} is obtained by deducting the cumulative timber loss due to hurricanes from the total biomass volume, which would accumulate under normal growth and no hurricanes. η_i is the number of normal rotations, such that the harvest is not affected by hurricanes. Additional timber might be available for sale in years in which a hurricane strikes, represented by the estimated volume K_{it} per acre. The term K_{it} represents the cumulative quantity of sale of salvaged timber per acre from *m* hurricanes in each region:

$$K_{it} = \sum_{j=1}^{m} K_{itj} \text{ , where } K_{itj} = k\, \overset{j}{d}_{it} \left(G_{it} - \sum_{w=1}^{j-1} K_{itw} \right)$$

where, $j \equiv w = 1, 2, 3 \ldots m$ … (17)

Planting occurs at the beginning of the project, following normal harvests or following a hurricane.

Land Value

L_i represents per unit cost of acquiring land in each of the regions. The amount of land acquired in each of the regions is decided at the beginning of the project period. It is assumed that land prices remain constant during the investment period and that land is not bought or sold after the initial investment decision has been made. W_0 refers to the risk free initial wealth that the landowner has to purchase land in each region and is thus a constraint.

$$\sum_{i=1}^{n} L_i A_i \leq W_0 \qquad \ldots (18)$$

L_i, which is the per unit price of land at the time of stand establishment, is estimated by the expected net present value of returns at the end of the 100-year planning horizon assuming the stand is planted in year 1 and replanted after harvest or hurricanes. L_i represents the maximum a risk neutral investor would be willing to pay for land.

Solving the Conceptual Model

In order to derive the optimal portfolio choice we need to derive an expression for the expected return and variance of returns, *x*. The model is solved for the RAFL. The expected value of returns in region '*i*', given that the binary random variable, y_{it}, takes on value 1 when there are one or more hurricanes in a given period and value 0 in years with no hurricanes, is given by:

$$E(x) = E\left(\sum_{i=1}^{n} Q_i\right) \qquad \ldots (19)$$

Expected returns in region *i* are given by:

$$E(Q_i) = E\left(\left(\sum_{t=1}^{T} \frac{\left(pB_{it} - py_{it}M_{it} + qy_{it}K_{it} - Z\right)}{(1+r)^t} + \eta_i \frac{qJ_{iV_i}}{(1+r)^{V_i}} - \sum_{i=1}^{n} C_i\right) A_i\right)$$

Using,

$$Z = -H_i - y_{it}S_i - y_{it}F_i - y_{it}N_i$$

$$J_{iV_i} = G_{it} - \sum_{t} y_{it}O_{it}$$

Variance of landowner's profits in region '*i*' is given by:

$$\sigma_{Q_i}^2 = Var\{Q_i\}$$

$$= Var\left(\left(\sum_{t=1}^{T} \frac{\left(pB_{it} - py_{it}M_{it} + qy_{it}K_{it} + Z\right)}{(1+r)^t} + \eta_i \frac{qJ_{iV_i}}{(1+r)^{V_i}} - \sum_{i=1}^{n} C_i\right) A_i\right)$$

$$= E\{Q_i - E(Q_i)\}^2$$

Where $Q_i = \left(\sum_{t=1}^{T} \frac{\left(pB_{it} - py_{it}M_{it} + qy_{it}\, K_{it} + Z \right)}{(1+r)^t} + \eta_i \frac{qJ_{iV_i}}{(1+r)^{V_i}} - \sum_{i=1}^{n} C_i \right) A_i$

$$\sigma_{Qi}^2 = A_i^{\,2} E\left((y_{it} - \pi_{it}) \left(\sum_{t=1}^{T} \frac{\left(-pM_{it} + q\,K_{it} - S_i - F_i - N_i \right)}{(1+r)^t} - \eta_i \frac{q(\sum_t O_{it})}{(1+r)^{V_i}} \right) \right)^2$$

π_{it} is the expected value of y_{it}.

$$\sigma_{Qi}^2 = A_i^{\,2} \left(\pi_{it}(1-\pi_{it}) \right) X_i \qquad \ldots (20)$$

Where

$$X_i = \left(\sum_{t=1}^{T} \frac{\left(-pM_{it} + q\,K_{it} - S_i - F_i - N_i \right)}{(1+r)^t} \right)^2 + \left(\eta_i \frac{q(\sum_t O_{it})}{(1+r)^{V_i}} \right)^2$$
$$- 2\eta_i \frac{q(\sum_t O_{it})}{(1+r)^{V_i}} \sum_{t=1}^{T} \frac{\left(-pM_{it} + q\,K_{it} - S_i - F_i - N_i \right)}{(1+r)^t}$$

Thus the certainty equivalent of profits for the landowner in all '*i*' regions is given by:

$$\mathrm{CE}\ (\mathrm{x}) = \sum_{\mathrm{i}=1}^{\mathrm{n}} \mathrm{E}\ (\mathrm{Q_i}) - \frac{\lambda}{2} Var\left(\sum_{i=1}^{n} Q_i \right)$$

$$\mathrm{CE}\ (\mathrm{x}) = \sum_{\mathrm{i}=1}^{\mathrm{n}} \mathrm{E}\ (\mathrm{Q_i})\ - \frac{\lambda}{2} \left[\sum_{i=1}^{n} Var(Q_i) + 2 \sum\sum_{i<j} Cov(Q_i, Q_j) \right]$$

The first order conditions for utility maximization for the landowner will maximize the certainty equivalent in all regions:

$$\underset{A_i}{Max}\ \mathrm{CE\ (x)}$$

$$\underset{A_i}{Max}\ E\left(\sum_{i=1}^{2} Q_i\right) - \frac{\lambda}{2}\left[\sum_{i=1}^{n} Var(Q_i) + 2\sum\sum_{i<j} Cov(Q_i, Q_j)\right] \quad \ldots (21)$$

Subject to:

$$\sum_{i=1}^{n} L_i A_i \leq \mathrm{W}_0$$

$$A_i \geq 0$$

For computational ease and without loss of generality in order to derive the first order conditions (FOCs) it is assumed that there are only two regions, i.e. $i = 2$.

The covariance of returns in different regions is given by:

$$\sum_i \sum_j \underset{i<j}{Cov}(Q_i, Q_j) = \sum_i \sum_j E\left[(Q_i - E(Q_i))(Q_j - E(Q_j))\right]$$

$$Cov(Q_1, Q_2) = E\left[(Q_1 - E(Q_1))(Q_2 - E(Q_2))\right]$$

$$Cov(Q_1, Q_2) = A_1 A_2 W_1 W_2 N_{12} \quad \ldots (22)$$

Where $W_i = \left(\sum_{t=1}^{T} \frac{\left(-pM_{it} + qK_{it} - S_i - F_i - N_i\right)}{(1+r)^t} - \eta_i \frac{q(\sum_t O_{it})}{(1+r)^{V_i}} \right)$

And $N_{12} = E\left[\{(y_{1t} - \pi_{1t})\}\{(y_{2t} - \pi_{2t})\}\right]$

Then the certainty equivalent of net revenues is give by:

$$Y = \sum_{\mathrm{i}=1}^{2} \mathrm{E\ (Q_i)} - \frac{\lambda}{2}\left[\sum_{i=1}^{2} Var(Q_i) + 2\sum\sum_{i<j} Cov(Q_i, Q_j)\right]$$

or,

$$Y=\sum_{t=1}^{T}\left[A_1U_1+A_2U_2\right]-\frac{\lambda}{2}\left[\sum_{t=1}^{T}\left\{A_1^{\,2}\left(\pi_{1t}(1-\pi_{1t})\right)X_1+A_2^{\,2}\left(\pi_{2t}(1-\pi_{2t})\right)X_2+2A_1A_2W_1W_2N_{12}\right\}\right]$$

Where,

$$U_i=\sum_{t=1}^{T}\frac{\left(pB_{it}-p\pi_{it}M_{it}+q\pi_{it}K_{it}-H_i-\pi_{it}S_i-\pi_{it}F_i-\pi_{it}N_i\right)}{(1+r)^t}+\eta_i\frac{q(G_{it}-\sum_t\pi_{it}O_{it})}{(1+r)^{V_i}}-\sum_{i=1}^{n}C_i$$

The Lagrangian is given by:

$$L=Y+\lambda_1(W_o-L_1A_1-L_2A_2) \qquad \ldots (23)$$

The necessary conditions for non-linear problems with equality and inequality constraints have been developed by Kuhn and Tucker. Kuhn-Tucker conditions are necessary conditions only if the constraint qualification is satisfied. Constraint qualification refers to conditions on the constraint functions that are sufficient to make the Kuhn-Tucker conditions (for inequality constraints) valid (Chiang). Kuhn-Tucker Sufficiency theorem is automatically satisfied for the linear constraints, i.e., the constraint qualification is satisfied, thus ensuring that Kuhn-Tucker conditions are necessary and sufficient (Chiang). The first order Kuhn-Tucker conditions are given by:

$$(1)\frac{\partial L}{\partial A_1} = \sum_{t=1}^{T}[U_1] - \frac{\lambda}{2}\sum_{t=1}^{T}[2A_1(\pi_{1t}(1-\pi_{1t}))X_1 + 2A_1W_1W_2N_{12})] - \lambda_1 L_1 \le 0$$
$$(2)A_1 \ge 0$$
$$(3)A_1\frac{\partial L}{\partial A_1} = 0$$
$$(4)\frac{\partial L}{\partial A_2} = \sum_{t=1}^{T}[U_2] - \frac{\lambda}{2}\sum_{t=1}^{T}[2A_2(\pi_{2t}(1-\pi_{2t}))X_2 + 2A_2W_1W_2N_{12})] - \lambda_1 L_2 \le 0$$
$$(5)A_2 \ge 0$$
$$(6)A_2\frac{\partial L}{\partial A_2} = 0$$
$$(7)\frac{\partial L}{\partial \lambda_1} = W_o - L_1A_1 - L_2A_2 \ge 0$$
$$(8)\lambda_1 \ge 0$$
$$(9)\lambda_1\frac{\partial L}{\partial \lambda_1} = 0$$

The conditions (1), (4), and (7) are the marginal conditions corresponding to each A_i and λ_i. In addition, A_1, A_2, λ_1 must be non-negative as well. Each of these variables is also characterized by a complementary slackness condition as shown in (3), (6) and (9). This means for each A_i an optimal solution must be found such that either the marginal condition holds as equality, or the choice variable in question must take a zero value, or both. Similarly, for each of the λ_i an optimal solution must be found such that either the marginal condition holds as equality – meaning that the constraint is exactly satisfied, or the Lagrange multiplier in question becomes zero, or both.

A more explicit interpretation of Kuhn Tucker conditions is as follows:

1. $\sum_{t=1}^{T}[U_1] - \frac{\lambda}{2}\sum_{t=1}^{T}[2A_1(\pi_{1t}(1-\pi_{1t}))X_1 + 2A_1W_1W_2N_{12})]$ = the marginal certainty equivalent net present value of returns in region 1

2. $\sum_{t=1}^{T}[U_2]-\frac{\lambda}{2}\sum_{t=1}^{T}[2A_2(\pi_{2t}(1-\pi_{2t}))X_2+2A_2W_1W_2N_{12})]$= the marginal certainty equivalent of net present value of returns in region 2
3. λ_1 = shadow price of wealth/capital constraint
4. L_1 = the amount of wealth used up in acquiring the marginal unit of land in region 1
5. $\lambda_1 L_1$ = the marginal imputed cost of wealth/capital incurred in acquiring the marginal unit of land in region 1.

The marginal condition $\frac{\partial L}{\partial A_1}$ requires that the marginal certainty equivalent of net present value of returns from land in region 1 be no greater than its marginal imputed cost, i.e., no under-imputation is permitted (Chiang). According to the corresponding complementary slackness condition if under the optimal solution a non-zero amount of land is brought into production (A_1>0), then the marginal certainty equivalent of net present value of returns must be exactly equal to the marginal imputed cost ($\frac{\partial L}{\partial \overline{A}_1}$=0, where, $\overline{A}_1$ is the optimal value of land in region 1). A similar interpretation can be made for the FOCs in region 2. If, however, the marginal imputed cost is greater than the marginal net present value of returns ($\frac{\partial L}{\partial \overline{A}_1}$<0) in the optimal solution, then no land should be acquired in region 1 ($\overline{A}_1$=0). The marginal condition $\frac{\partial L}{\partial \lambda_1}$ implies that the entrepreneur should remain within the bounds of the wealth constraint. The corresponding complementary slackness condition then implies that in case the wealth is not completely utilized in the optimal solution ($\frac{\partial L}{\partial \bar{\lambda}_1}$>0), then the shadow price of wealth constraint has to be equal to zero in the optimal solution since it is not allowed to be negative ($\bar{\lambda}_1$=0). If, however, the shadow price is positive ($\bar{\lambda}_1$>0) in the optimal solution, then the wealth resource is completely utilized in the optimal solution ($\frac{\partial L}{\partial \bar{\lambda}_1}$=0). The Lagrange multiplier $\bar{\lambda}_1$ can also be interpreted to be a measure of how the optimal value of the objective function reacts to a marginal relaxation of the wealth constraint. Considering the complementary slackness condition if the wealth constraint is not binding in the optimal solution ($\frac{\partial L}{\partial \bar{\lambda}_1}$>0), then relaxing this constraint marginally will have no impact on the optimal value of the objective function ($\bar{\lambda}_1$=0). If, however, relaxing the wealth constraint marginally (increasing the initial wealth) does increase the net present value of returns ($\bar{\lambda}_1$>0), then the wealth constraint must be binding in the optimal solution ($\frac{\partial L}{\partial \bar{\lambda}_1}$=0).

Empirical Model

In this section we provide empirical specification of the components of the forestry returns model.

Hurricane Landfall Probability

Historical North Atlantic Tropical Cyclone Tracks, 1851-2003, created by National Oceanic and Atmospheric Administration, Tropical Prediction Center/National Hurricane Center (http://hurricane.csc.noaa.gov/hurricanes/download.html) are used to estimate the average number of storms in the three regions from 1889 to 1989, the last year in the data set. Historically the coast in the state of South Carolina has a 16% probability of getting hit by a hurricane in a given year, the piedmont has a 7% probability and the upland has a 3% likelihood of hurricane strike in a year. We considered all hurricanes on the Saffir-Simpson hurricane scale for developing our data set. The Saffir-Simpson scale is a 1-5 rating based on the hurricane's intensity (Table 2). The scale is assigned to a hurricane based on its peak wind speed. Category No. 1 begins with hurricanes in which the maximum sustained winds are at least 74 miles per hour, while Category No. 5 applies to hurricanes with maximum sustained winds of 155 mph or more (http://www.nhc.noaa.gov/aboutsshs.shtml).

Table 2: The Saffir-Simpson Hurricane Scale

Saffir-Simpson scale Category	Definition	Effects
One	Winds 74-95 mph	No real damage to building structures. Damage primarily to unanchored mobile homes, shrubbery, and trees. Also, some coastal road flooding and minor pier damage
Two	Winds 96-110 mph	Some roofing material, door, and window damage to buildings. Considerable damage to vegetation, mobile homes, and piers. Coastal and low-lying escape routes flood 2-4 hours before arrival of center. Small craft in unprotected anchorages break moorings.
Three	Winds 111-130 mph	Some structural damage to small residences and utility buildings with a minor amount of curtain wall failures. Mobile homes are destroyed. Flooding near the coast destroys smaller structures with larger structures damaged by floating debris. Terrain continuously lower than 5 feet ASL may be flooded inland 8 miles or more.
Four	Winds 131-155 mph	More extensive curtain wall failures with some complete roof structure failure on small residences. Major erosion of beach. Major damage to lower floors of structures near the shore. Terrain continuously lower than 10 feet ASL may be flooded requiring massive evacuation of residential areas inland as far as 6 miles.
Five	Winds greater than 155 mph	Complete roof failure on many residences and industrial buildings. Some complete building failures with small utility buildings blown over or away. Major damage to lower floors of all structures located less than 15 feet ASL and within 500 yards of the shoreline. Massive evacuation of residential areas on low ground within 5 to 10 miles of the shoreline may be required.

Source: http://www.nhc.noaa.gov/aboutsshs.shtml

The historical hurricane landfall probabilities are input into @Risk for simulating random hurricane strikes in each region. Storms are assumed to occur independently of each other per time period but not spatially. Using the historical data on hurricane landfall in the state of South Carolina from 1889 – 1989 the estimated correlation between probability of hurricane landfall in the coast and piedmont regions is 0.629, between the piedmont and upland regions is 0.641 and between the coast and upland regions is 0.403.

Forest Biomass Yield

This paper focuses on one predominant species of trees in the region of study, loblolly pine. The planting density is assumed to be 750 trees per acre in all three regions. The site indices for the three regions were obtained from the FIA data on loblolly pine in South Carolina by taking a weighted average of the site indices in all the counties for the three regions under consideration. The site indices were weighted by the average number of acres of land in each site index class. The site indices obtained from the FIA data for base age 25 are 68, 62 and 58 for the coast, piedmont and upland regions, respectively. G_{it} represents biomass volume in cubic feet, which was converted into board feet for calculating timber returns and into cords for calculating pulpwood returns (Timber Mart South). It is assumed that the marginal increase in biomass volume per acre becomes zero at age 35 for the coast, at age 38 for the piedmont and at age 41 for the upland (Personal Communication, Greg Amacher and Stephen Prisley, Department of Forestry, Virginia Tech). Following a hurricane the biomass grows to the level it would have grown to without the hurricane unless a hurricane leads to higher than 40% damage to the stand, in which case the landowner clears the stand and re-plants (Table 3). The model is designed to take account of the damage-salvage scenarios presented in Table 3.

Table 3: Hurricane Damage – Tree Salvage Scenarios

		DAMAGE		
		0-20%	**20-40%**	**40% +**
AGE	**0-8**	Do Nothing	Do Nothing	Re – Site Prep & Re – Planting
	8-Merchantable Age	Do Nothing	Pre-commercial Thin	Re – Site Prep & Re – Planting
	Merchantable Age +	Do Nothing	Salvage	Harvest, Site – Prep & Replanting

Carbon Conversion

The biomass is converted into carbon dioxide equivalents in a four-stage process. First, growing-stock volume is converted to total forest tree volume by multiplying by a biomass expansion factor of 1.408 (Birdsey, 1992) to account for the additional tree volume excluded from estimates of growing-stock volume: tops and branches, foliage, rough and rotten trees, small trees, standing dead trees, stump sections, roots, and bark. Second, total tree volume in cubic feet is converted to carbon in pounds. One cubic foot of wood is assumed to be equal to 16.9 pounds of carbon (Birdsey, 1992). Third, the carbon volume in pounds is converted into carbon volume in metric tons. Fourth, carbon volume is converted into carbon dioxide equivalents by multiplying carbon equivalents by 44/12 (the ratio of the molecular weight of carbon dioxide to carbon). Only above ground biomass is considered as the relevant carbon sink. Carbon in forest soil and below ground woody material in trees, litter from under story plants and debris on forest floor is not considered.

Hurricane Damage

It is assumed that any hurricanes that strike prior to the merchantable age, a_i, which is assumed to be 15 in coastal region, 18 in piedmont region and 21 in upland region, do not leave any merchantable salvaged timber. Damage probabilities for each of the regions are randomly generated from hurricane HUGO data in South Carolina based on the damage in various counties in the coast, piedmont and upland and are presented in Table 4:

Table 4: Damage to forest from hurricane HUGO by counties per region

Coast	**Proportion of Damage**	**Piedmont**	**Proportion of Damage**	**Upland**	**Proportion of Damage**
Horry	0.023	Marlboro	0.028	Fairfield	0.003
Marion	0.067	Richland	0.036	York	0.031
Orangeburg	0.090	Dillon	0.074	Chester	0.110
Florence	0.127	Kershaw	0.174	Lancaster	0.354
Georgetown	0.148	Darlington	0.207	Chesterfield	0.106
Dorchester	0.170	Lee	0.342		
Williamsburg	0.252	Sumter	0.442		
Charleston	0.472	Clarendon	0.453		
Berkeley	0.490				

Source: Modified from Sheffield and Thompson

The proportion of marginal damage d_{it}^{j} from the j^{th} hurricane in a given year is generated randomly from a distribution estimated for each region (Table 5). Mean values from hurricane HUGO data (Table 4) in each of the regions are used to estimate damage proportions for each of the regions, which are randomly generated using the software 'Best Fit' (Palisade Corporation, http://www.palisade.com/html/bestfit.asp).

Table 5: Hurricane Damage Proportions

Region	Distribution	Mean Damage
Coast	Log Logistic	24.5%
Piedmont	Uniform	24%
Upland	Inverse Gaussian	12%

Damage proportions were assumed to be independent between regions and years. From Table 3, in case the cumulative damage from *m* hurricanes in a given year is less than 20% of the total standing biomass, the landowner does not take any action to salvage or clear the damage. In case the cumulative damage from hurricanes in a given year is between 20% and 40% and the age of forest stand is between 0-8 years, the landowner does not take any action to salvage or clear the damage. If the forest age is between 8 years and the merchantable age, then the landowner incurs a cost, $100 per acre, for undertaking pre-commercial thinning. If the age of forest stand is above merchantable age, then the landowner salvages the downed biomass. In case the damage is greater than 40% and the age of forest stand is less than the merchantable age, then the landowner incurs cost for re-site preparation and re-planting and nothing is salvaged. In case the damage is greater than 40% and the age of stand is greater than the merchantable age, the landowner salvages the downed biomass, harvests the remaining stand, and starts a new plantation. In that case the amount of harvest equals the undamaged stand plus the salvaged proportion of damaged stand.

The coefficients ε_{1t} and ε_{2t} (equation 8) represent the average proportions of timber and pulpwood, respectively, by age (Table 6). Table 6 shows the assumed values of average proportions of sawtimber by age for the three site indices 68, 62 and 58 at base age 25. The remaining proportion of wood is assumed to be pulpwood.

Table 6: Sawtimber Proportions by Age

	Site Index		
Age	**Coast (Site Index=68)**	**Piedmont (Site Index =62)**	**Upland (Site Index = 58)**
15	0.68	0	0
18	0.73	0.68	0
21	0.77	0.73	0.68
24	0.77	0.77	0.73
27	0.81	0.77	0.77
31	0.83	0.81	0.77
>35	0.85	0.83	0.81

For the present research it is assumed that the proportion of downed forest biomass (timber) that is salvaged and converted into wood products, *k*, is 15.5 %. This figure is based on the estimate for salvage presented by Lupold for Hurricane Hugo in South Carolina. The assumption is based on the premise that some amount of carbon content is lost in the process of salvaging during hurricane years, since wood in the form of small branches which does not have much economic value might be left to rot. From Birdsey (1996) we assume that percentage of carbon sequestered in sawtimber in the year of harvest, e_1, is 47.2% and in pulpwood, e_2, is 30.1% (see equation 8).

The calculation of the proportion of carbon emitted as a result of hurricanes can be understood using simple examples. If a hurricane leads to 30% damage to the standing forest in a given year and the age of the forest is below merchantable age, then nothing is salvaged, no wood products are created, and the proportion of damage to stored carbon is 30%, i.e., d_{it}^{1} = 0.30. If the age of the forest is above merchantable age and a hurricane leads to 20% damage to the standing forest, then nothing is salvaged, no wood products are created and d_{it}^{1} = 0.20. If the forest is above merchantable age and damage from hurricane to the standing forest is 30%, then 15% of the downed biomass is salvaged (k = 0.15), e_1 = 0.472, e_2 = 0.301, ε_{1t} = 0.68 and ε_{1t} = 0.32. The actual proportion of carbon emissions is thus equal to 0.30*(0.68*(1-0.15*0.472) + 0.32*(1-0.15*0.301)) = 0.28.

Optimal Rotation Age

The optimal rotation age, V_i, under both SCPL and RAFL in each region is that which maximizes the expected net present value of returns over the planning horizon (T = 100 years) in each region.

Carbon Offset Price

The right to emit carbon in the form of carbon offsets generated from terrestrial sequestration will have a market determined “price” once the carbon trading markets become operational both in U.S. and other countries. The price of emissions reductions is influenced by a variety of factors including regulatory uncertainty, project specification (whether permanent or temporary carbon offsets), and technical risks, supply quantities, buyer outlook, and current market activity. It is likely that the value assigned by the market to temporary carbon sequestration offsets is lower as compared to the value of permanent emission reduction credits which might result from reduction in fossil fuel usage. Temporary credits are cheaper because the buyer of temporary carbon offsets would be liable to replace those offsets at the end of the short-term contract period with either more temporary offsets or permanent offsets. Carbon markets are not currently formally established in U.S. Furthermore, in a world where carbon offsets are traded, the market would assign the price/value of a permanent carbon offset. This would provide a base price from which annual rental values for carbon sequestration services could be determined, depending on discount rate and other costs that might be unique to temporary sequestration projects like monitoring and verification costs (Marland et al.).

It is assumed that price for temporary carbon offsets has been market determined and given to the landowner. Price of temporary offsets is likely to be much lower than GHG permits generated by permanent emissions reduction (e.g., reduction in fossil fuel usage). Permanent carbon credits are currently being traded in the European Union since 16 February 2005, when the Kyoto Protocol entered into force. The current trading price of carbon dioxide equivalents as of May 12th 2005 is €16.40/ ton of CO_2 equivalents (www.pointcarbon.com). This is equivalent to approximately \$20.00/ ton of CO_2 equivalents. Price of permanent reductions will have to be discounted in order to derive the annualized value of temporary emission reductions. Using the 5% risk-free rate of time preference we arrived at the discounted annualized value of temporary carbon reductions at \$1.00/ ton of CO_2 equivalents per year. Price of emissions allowance is likely to be lower during Kyoto Protocol's first commitment period (2008-2012) than current prices due to increase in the number of market participants and large scale power sector abatement and fuel switching (Karmali). In order to analyze the sensitivity of landowners' decisions to different carbon offset (CO_2 equivalents) prices we consider carbon prices of $0.00, $0.10 and $1.00 per sequestered ton of CO_2 equivalents per year.

Lumber Price

Stumpage prices are reported net of logging and transportation costs. Based on prices available from Timber Mart South (http://www.tmart-south.com/tmart/) the average pulp wood (2004) price is $6.53 per ton ($17.50/cord) and average timber price for the same period is $38.00 per ton ($285.90/ thousand board feet). Timber prices may be affected following a hurricane (Prestemon and Holmes). If hurricanes damage a lot of timber causing many landowners to attempt to salvage their timber, the logging costs will rise (everyone suddenly wants to hire a logger) and wood prices would likely be depressed as a flood of timber hits the market. Thus, usually only the most valuable timber (near rotation age) and largest blocks (where harvesting cost per unit is lower) would likely be selected for salvage. Prestemon and Holmes estimate that in the short run (in the quarter immediately after hurricane strike) saw timber stumpage prices following hurricane HUGO in South Carolina's piedmont dropped by $5.10 to $10.50 per cubic meter (21% to 36%) and in South Carolina's coastal plain dropped by $10.20 to $11.20 per cubic meter (29% to 30%). They also estimate a long-run enhancement effect which is a result of large reductions in timber stocks that can lead to a price shift due to increasing timber scarcity and enhancement in value of remaining stocks. For South Carolina's piedmont the implied long-run price increase ranged from about $3.80 to $7.60 per cubic meter (18% to 32%). For South Carolina's coastal plain, the implied long-run value enhancement ranged from $2.50 to $4.30 per cubic meter (6% to 12%).

Prestemon and Holmes suggest that these enhancement effects, which result in an increase in value of the undamaged timber following natural disasters, may act to a degree to reduce the investment disincentives due to risk of carbon emissions and biomass loss from hurricanes (and other natural disasters) for owners with geographically diversified holdings. "If timberland holdings are geographically diversified, timberland owners are less subject to natural hazard risk as a proportion of their entire holdings and, in addition, are more likely to experience enhancement effects if catastrophic damage is incomplete and non-homogeneous." (Prestemon and Holmes, p. 158). Thus small forest-land owners with one or a few forest parcels who are not geographically diversified (or risk averse landowners) are likely to have higher disincentives for participation and be less likely to realize enhancement benefits. This would be especially true if the "small" landowner or the risk averse landowner own land in regions that have been or have high likelihood of being affected by hurricane damage. The presence of enhancement effects may or may not be sufficient for these categories of landowners to participate in carbon offset trading markets.

Based on estimates presented by Prestemon and Holmes, we assume that hurricanes lead to a 30% decline in timber prices in hurricane years in all three regions. It is assumed that the enhancement effect results in an increase in value of the undamaged timber following natural disasters such that the prices return to pre-hurricane levels in the following year.

Site Preparation and Planting Cost

The estimates for site preparation and planting costs following a hurricane are available for hurricane HUGO in the state of South Carolina (Straka et al.). Costs are expressed in 2004 dollars using a 2.68% annual inflation factor between 1995 and 2004. Site preparation cost on conventional sites or following a normal harvest is assumed to be \$63.00 per acre and site preparation cost following hurricanes is \$76.00 per acre. The tree planting cost is assumed to be \$46.00 per acre on both conventional and hurricane affected sites.

Monitoring and Verification costs

To the extent that sequestered carbon or emission reduction attains a value (i.e. a “creditable” ton), it becomes a commodity. Unlike other commodities, however, it does not move physically from the control of the supplier to the control of the buyer. Instead, what moves is a certificate or statement proclaiming the existence, stability, and legitimacy of the claim. To be fully credible, that claim must be subject to monitoring and verification.

We use the estimated annual monitoring and verification costs of Mooney et al. for non-contiguous parcels, which involve extra costs for the added distance and time in traveling to various sampling sites. Mooney et al. use a “risk factor” of 15% as a cost buffer for non-contiguous parcels in case some unpredictable events occur. We use the cost of \$4.57/acre for non-contiguous parcels with the risk assumption in years when there is at least one hurricane in a region and the cost of \$3.98/acre when there are no hurricanes in a given region.

Simulation and Optimization Model

@Risk software offered by Palisade Corporation is used to generate simulation data on expected returns from forestry and carbon offset sales under different accounting and liability scenarios using Monte Carlo simulations. We run 1000 iterations to generate data on net present value of returns in coast, piedmont and upland under different carbon price scenarios. The risk profiles for hurricane risk and corresponding damages to forest stand are specified using @Risk and the simulations are run to derive the distribution of net returns over the planning horizon. The simulation data are used to estimate the variance-covariance matrix of returns between the three regions, the expected net present value of returns, the optimal rotation ages in three regions and land prices. These data are input into a quadratic programming model, which is solved using General Algebraic Modeling System (GAMS), to determine the optimal amount of land that the landowner will invest in the three regions under various scenarios. Equation (11), the objective function, is maximized to determine the optimal amount of land A_i that the landowner invests in at the beginning of the planning horizon subject to the land constraint equation (18). The optimal amount of land is estimated for different levels of risk aversion for the forest landowner by parametrically changing the risk aversion coefficient λ between zero for a risk neutral landowner to 80 for a highly risk averse landowner (McCarl and Spreen). These data are then used to develop the mean-variance efficient frontier for the landowner. It is assumed that the landowner has an initial risk free wealth of $500,000.

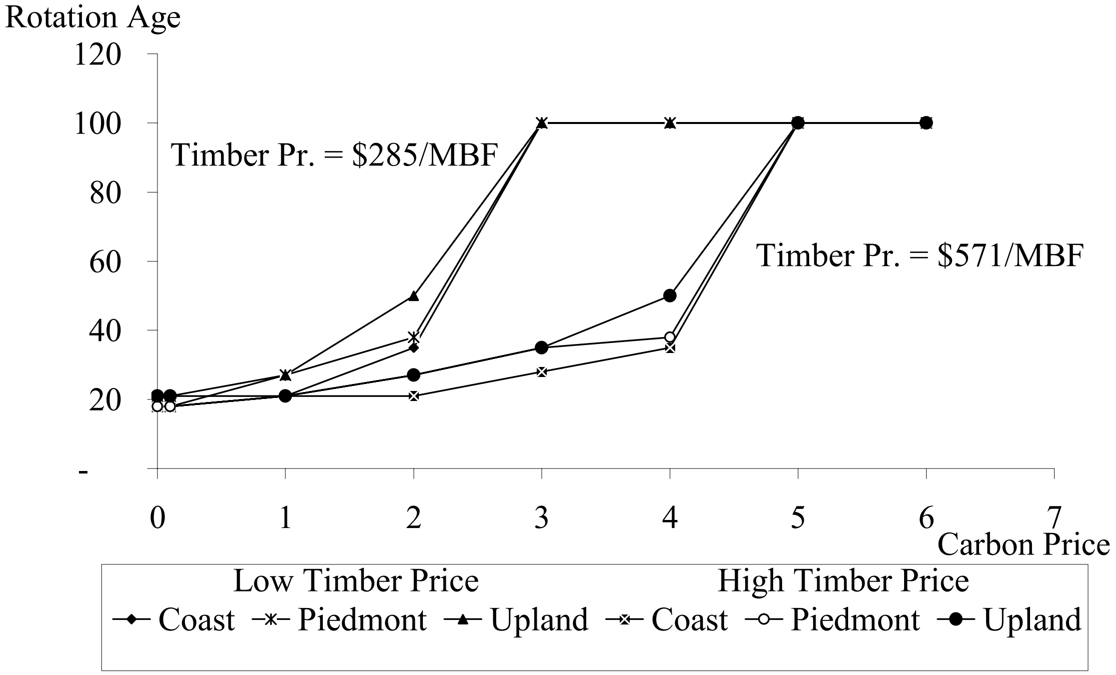
Results and Discussion

This section presents the results of our simulation model for the optimal rotation age, net present values and optimal land investment.

Rotation Age

The baseline scenario considered is \$0.00/ton CO_2 equivalents, i.e., landowner receives returns only from timber. In this case both the SCPL and RAFL generate the same results because no carbon returns are earned. The rotation ages at which the net present value of returns from timber is maximized for both SCPL and RAFL are 18, 18 and 21 years in the coast, piedmont and upland regions, respectively. As carbon prices increase, the rotation age increases under both scenarios. Figure 3 presents the optimal rotation age under RAFL scenario, with different carbon and timber prices. When we increased the timber price from \$285/thousand board feet (MBF) to \$571/MBF, the optimal rotation age is lowered for carbon prices of \$2.00 to \$5.00 per ton of CO_2 equivalents. However, for prices above \$5 per ton CO_2 equivalents the rotation age is 100 years for both timber prices.

Figure 3: Optimal Rotation Age with RAFL Payment Scheme and Varying Carbon Prices and Timber Prices



Under the SCPL scenario, rotation age converges to 100 years or higher (for both timber prices) faster than under RAFL, reflecting the fact that carbon returns outweigh timber returns for lower carbon prices under SCPL (Table 7). Under both approaches, the landowner has an incentive to delay the timber harvest for as long as possible in all three regions even at very low carbon prices.

Table 7: Rotation Age, Effect of Carbon Price vs. Timber Price

	Timber Price = $285/MBF						Timber Price = $571/MBF					
	RAFL			SCPL			RAFL			SCPL		
CO_2e[a] Price	***C*[b]**	***P*[c]**	***U*[d]**	***C***	***P***	***U***	***C***	***P***	***U***	***C***	***P***	***U***
$ 0.00	18	18	21	18	18	21	18	18	21	18	18	21
$ 0.10	18	18	21	18	18	21	18	18	21	18	18	21
$ 1.00	21	27	27	100	100	100	21	21	21	21	21	27
$ 2.00	35	38	50	100	100	100	21	27	27	100	100	100
$ 3.00	100	100	100	100	100	100	28	35	35	100	100	100
$ 4.00	100	100	100	100	100	100	35	38	50	100	100	100
$ 5.00	100	100	100	100	100	100	100	100	100	100	100	100

[a] Carbon Dioxide Equivalent
[b] Coast
[c] Piedmont
[d] Upland

NPV and Optimal Level of Land Investment

Table 8 and Table 9 present the certainty equivalent (CE) of net present value (NPV) of returns per acre over a 100-year planning horizon under all simulation scenarios for SCPL and RAFL, respectively. For prices of $0.10 and $1.00/ton CO_2 equivalents, the certainty equivalent per acre is higher under SCPL for all three regions and for all levels of risk aversion because the carbon returns accrue earlier in the planning horizon under SCPL as compared to RAFL.

Table 8: SCPL - Certainty Equivalent of Returns ($) per Acre for Varying Risk Aversion – Individual Regions

	$0.00/ton CO_2e			**$0.10/ton CO_2e**			**$1.00/ton CO_2e**		
RA[a] (λ)	***Coast***	***Piedmont***	***Upland***	***Coast***	***Piedmont***	***Upland***	***Coast***	***Piedmont***	***Upland***
0.000	1930	1714	1682	2051	1829	1820	6701	8269	9369
0.001	1721	1595	1656	1837	1709	1793	4168	7077	9053
0.005	884	1119	1550	982	1229	1686	-5967	2308	7791
0.025	-3300	-1264	1022	-3294	-1171	1148	-56642	-21536	1479

[a] Risk Aversion Coefficient

Table 9: RAFL - Certainty Equivalent of Returns ($) per Acre for Varying Risk Aversion – Individual Regions

	$0.00/ton CO_2e			**$0.10/ton CO_2e**			**$1.00/ton CO_2e**		
RA[a] (λ)	***Coast***	***Piedmont***	***Upland***	***Coast***	***Piedmont***	***Upland***	***Coast***	***Piedmont***	***Upland***
0.000	1930	1714	1682	2033	1807	1791	3019	2768	2910
0.001	1721	1595	1656	1816	1683	1763	2681	2555	2867
0.005	884	1119	1550	948	1189	1654	1331	1700	2694
0.025	-3300	-1264	1022	-3391	-1282	1105	-5421	-2574	1830

[a] Risk Aversion Coefficient

The CE of NPV per acre for the three regions under the baseline scenario of zero carbon price is the same under SCPL and RAFL for different levels of risk aversion. Under SCPL the coastal region has the highest CE per acre followed by piedmont and then upland for risk neutrality and a zero carbon price. The CE would depend on the site index for a given region, which determines biomass growth rate, and the risk of biomass damage. Higher biomass growth rates due to higher site index in the coast and piedmont outweigh the effect of hurricane risk. For modest risk aversion (λ=0.001), CE is highest for the coast, followed by upland and then piedmont. For higher levels of risk aversion (λ=0.005, λ=0.025), the upland has highest CE reflecting lower hurricane risk.

The trends for the \$0.10/ton CO_2 equivalents price are similar to those for \$0.00/ton CO_2 equivalents. At the \$1.00 carbon price, where carbon returns form a bigger proportion of total returns, the certainty equivalent is highest in the upland, followed by piedmont and then coast. Higher risk to carbon returns, which now form a much larger proportion of total returns, in the coast and piedmont outweighs the effect of higher growth rate in these regions with greater site indices. As the level of risk aversion increases, the CE of NPV is declining and becoming negative (the risk premium becomes larger than the mean of expected returns) due to higher variance of returns.

Under the RAFL for risk-neutrality and \$0.10/ton CO_2 equivalents (Table 9) the certainty equivalent is highest in the coast followed by piedmont and then upland. For risk-neutrality and \$1.00/ton CO_2 equivalents the certainty equivalent is highest in the coast followed by upland and then piedmont. For modest risk aversion (λ=0.001) and \$0.10/ton CO_2 equivalents, CE is highest for the coast, followed by upland and then piedmont. For higher levels of risk aversion (λ=0.005, λ=0.025), the upland has highest CE reflecting lower hurricane risk. For modest risk aversion (λ=0.001) and \$1.00/ton CO_2 equivalents, CE is highest for the upland, followed by coast and then piedmont. For higher levels of risk aversion (λ=0.005, λ=0.025), the upland has highest CE reflecting lower hurricane risk.

The risk neutral landowner is indifferent where land is bought, either with zero or non-zero carbon prices, because the land price is bid up to the expected NPV in each region. For a zero price for carbon offsets, the landowner would buy either 259 acres in the coast, 292 acres in the piedmont and/or 297 acres in the upland. As the level of risk aversion increases, the landowner diversifies into all three regions (Table 10 and Table 11) with highest level of land investment in the upland followed by piedmont and coast. When the carbon price increases to \$0.10/ton CO_2 equivalents for SCPL, the risk neutral landowner is indifferent between investing in 244 acres in the coast, or 273 acres in the piedmont, or 275 acres in the upland. At \$1.00/ton CO_2 for SCPL the risk neutral landowner is indifferent between investing in 75 acres in the coast, or 60 acres in the piedmont, or 53 acres in the upland. As the level of risk aversion increases, the landowner diversifies into all three regions with highest level of land investment in the upland followed by piedmont and coast. Hurricane risk is correlated across the three regions with the upland having the least likelihood of being hit by a hurricane, so as the level of risk aversion increases, the landowner is motivated to invest mostly in the upland because of higher variance of returns in the piedmont and coast. The land prices are increasing to reflect the additional returns from carbon; however, the risk averse landowner prefers to hold some idle wealth even with an initial wealth of \$500,000. The overall amount of land investment decreases with higher carbon prices due to an increase in variance of returns.

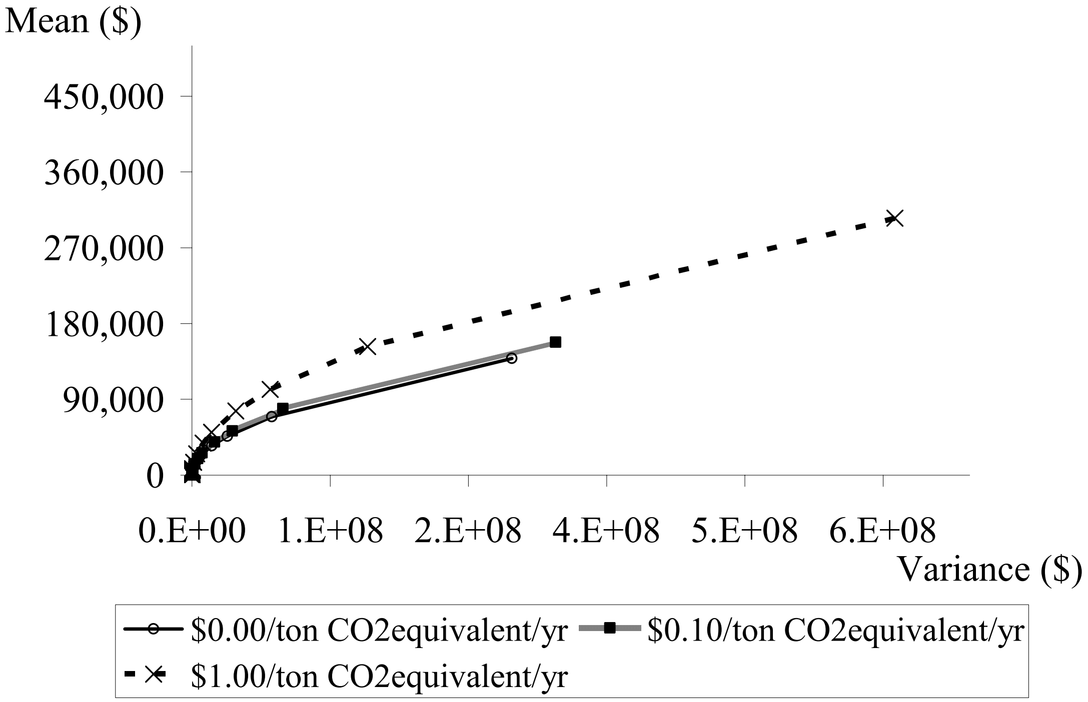
Table 10: SCPL Simulation Results – Optimal Land Investment and Certainty Equivalent of Returns [a]

	\$0.00/ton $\mathrm{CO_2}$e				**\$0.10/ton $\mathrm{CO_2}$e**				**\$1.00/ton $\mathrm{CO_2}$e**			
	$W_0=\$500{,}000$				**$W_0=\$500{,}000$**				**$W_0=\$500{,}000$**			
Risk Aversion Coefficient	***Coast (Acres)***	***Piedmont (Acres)***	***Upland (Acres)***	***Certainty Equivalent***	***Coast (Acres)***	***Piedmont (Acres)***	***Upland (Acres)***	***Certainty Equivalent***	***Coast (Acres)***	***Piedmont (Acres)***	***Upland (Acres)***	***Certainty Equivalent***
0.00025	8	12	61	69,394	8	13	65	78,914	1	4	27	152,551
0.00050	4	6	31	34,697	4	6	32	39,457	-	2	14	76,276
0.00075	3	4	20	23,131	3	4	22	26,305	-	1	9	50,850
0.00100	2	3	15	17,349	2	3	16	19,728	-	1	7	38,138
0.00150	1	2	10	11,566	1	2	11	13,152	-	1	4	25,425
0.00200	1	1	8	8,674	1	2	8	9,864	-	1	4	19,069
0.00300	1	1	5	5,783	1	1	5	6,576	-	-	3	12,713
0.00500	-	1	4	3,470	-	1	3	3,946	-	-	1	7,628
0.01000	-	-	2	1,735	-	-	2	1,973	-	-	1	3,814
0.01100	-	-	2	1,577	-	-	2	1,793	-	-	-	3,467
0.01250	-	-	2	1,388	-	-	2	1,578	-	-	-	3,051
0.01500	-	-	1	1,157	-	-	2	1,315	-	-	-	2,543
0.02500	-	-	1	694	-	-	1	789	-	-	-	1,526

[a] The mean and certainty equivalent for risk neutral decision maker is \$500,000. Variance for the risk neutral decision maker would depend on actual allocation of land among the three regions.

Figure 4 presents the mean variance (EV) frontier for different levels of risk aversion under various scenarios for the SCPL approach. Availability of non-zero carbon returns shifts the EV frontier upward and to the left. The returns to land have become more favorable, meaning that at any given level of risk (variance) the expected returns have increased. Similarly, an increase in carbon prices from $0.10 to $1/ton CO_2 equivalents per year shifts the EV frontier further to left.

Figure 4: SCPL - EV Frontier Over Positive Risk Aversion



Under the RAFL at a carbon price of $0.10/ton CO_2 equivalents a risk neutral landowner is indifferent between investing 246 acres of land in the coast, 277 acres in the piedmont, or 279 acres in upland. As the level of risk aversion increases, the landowner diversifies into all three regions with the highest level of land investment in the upland followed by piedmont and coast (Table 11). A similar trend can be seen at $1.00/ton CO_2 equivalents/yr. The total amount of land investment for risk averse decision maker with the payment of \$1.00/ton CO_2 equivalents is higher for RAFL as compared to SCPL due to lower land prices and lower variance of returns (See Tables 10 and 11). However, for \$0.10/ton CO_2 equivalents/yr the land investment for risk averse landowner is marginally higher under SCPL due to higher variance of returns (See Tables 10 and 11 below). Increasing risk-free wealth does not affect land investments for risk averse investors. With the availability of higher (\$800,000) initial risk-free wealth at \$1.00/ton CO_2 equivalents/yr; the overall level of land investment went up only for the risk-neutral investor.

Table 11: RAFL Simulation Results – Optimal Land Investment and Certainty Equivalent of Returns[12]

	\$0.00/ton CO_2e				**\$0.10/ton CO_2e**				**\$1.00/ton CO_2e**			
	W_0=\$500,000				**W_0=\$500,000**				**W_0=\$500,000**			
Risk Aversion Coefficient	***Coast (Acres)***	***Piedmont (Acres)***	***Upland (Acres)***	***Certainty Equivalent***	***Coast (Acres)***	***Piedmont (Acres)***	***Upland (Acres)***	***Certainty Equivalent***	***Coast (Acres)***	***Piedmont (Acres)***	***Upland (Acres)***	***Certainty Equivalent***
0.00025	8	12	61	69,394	8	12	62	75,300	8	10	65	121,494
0.00050	4	6	31	34,697	4	6	31	37,650	4	5	33	60,747
0.00075	3	4	20	23,131	3	4	21	25,100	3	3	22	40,498
0.00100	2	3	15	17,349	2	3	15	18,825	2	3	16	30,374
0.00150	1	2	10	11,566	1	2	10	12,550	1	2	11	20,249
0.00200	1	1	8	8,674	1	2	8	9,413	1	1	8	15,187
0.00300	1	1	5	5,783	1	1	5	6,275	1	1	5	10,125
0.00500	-	1	4	3,470	-	1	4	3,765	-	-	4	6,075
0.01000	-	-	2	1,735	-	-	2	1,883	-	-	2	3,037
0.01100	-	-	2	1,577	-	-	2	1,711	-	-	2	2,761
0.01250	-	-	2	1,388	-	-	2	1,506	-	-	1	2,430
0.01500	-	-	1	1,157	-	-	1	1,255	-	-	1	2,025
0.02500	-	-	1	694	-	-	1	753	-	-	1	1,215

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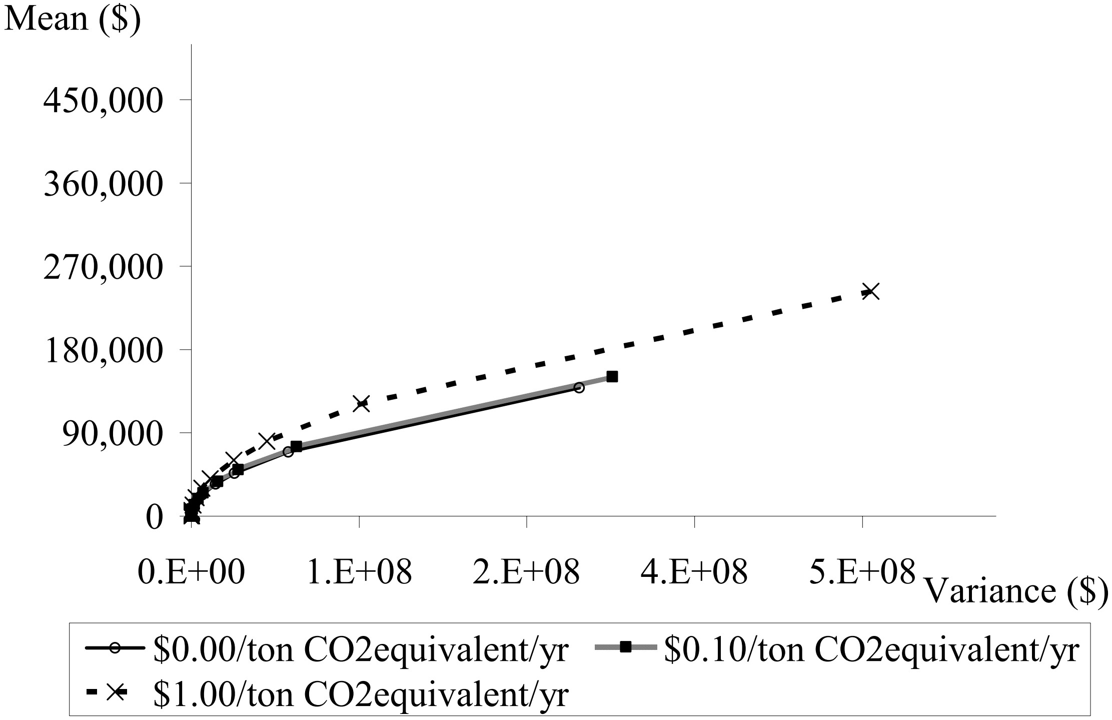
[12] The mean for risk neutral decision maker is \$500,000. Variance for the risk neutral decision maker would depend on actual allocation of land among the three regions.

Figure 5 presents the mean variance (EV) frontier for the different levels of risk aversion under various scenarios for the RAFL approach. Trends are similar to those for SCPL.

Figure 5: RAFL - EV Frontier Over Positive Risk Aversion



Sensitivity Analysis – Assuming Correlated Damages across Regions

Table 12 and Table 13 present the certainty equivalent (CE) of expected net present value (NPV) of returns per acre over a 100-year planning horizon under all simulation scenarios for SCPL and RAFL, respectively, with correlated damages across regions in a given period of time and assuming the landowner can invest in all three regions. The correlation is assumed to be the same as estimated correlation between probabilities of hurricane landfall identified earlier. The estimated correlation for damage proportions between the coast and piedmont regions is 0.629, between the piedmont and upland regions is 0.641 and between the coast and upland regions is 0.403.

The simulation results with correlated damages show that the certainty equivalents per acre are marginally higher for all three regions at a zero carbon price as compared to when no damage correlations were assumed (Table 8 and 9). Under SCPL (Table 12) with \$0.10/ton CO_2 equivalents/yr the CE is higher for the coast, piedmont and upland, except for the risk neutral in the coast. For \$1.00/ton CO_2 equivalents/yr the CE is marginally lower for the coast and piedmont and marginally higher for upland (compare with Table 8).

Table 12: SCPL - Certainty Equivalent of Returns (\$) per Acre for Varying Risk Aversion and Correlated Damages – Individual Regions

	\$0.00/ton CO_2e			**\$0.10/ton CO_2e**			**\$1.00/ton CO_2e**		
RA[a] (λ)	***Coast***	***Piedmont***	***Upland***	***Coast***	***Piedmont***	***Upland***	***Coast***	***Piedmont***	***Upland***
0.000	1930	1724	1699	2051	1838	1837	6653	8252	9405
0.001	1733	1611	1682	1848	1725	1820	4006	6983	9125
0.005	946	1158	1616	1039	1269	1752	-6583	1904	8005
0.025	-2989	-1104	1287	-3003	-1008	1414	-59526	-23487	2403

Under RAFL (Table 13) with \$0.10/ton CO_2 equivalents/yr the CE is higher for the coast, piedmont and upland, except for the risk neutral in the coast. For \$1.00/ton CO_2 equivalents/yr the CE is marginally higher for the coast, piedmont and upland (compare with Table 9).

Table 13: RAFL - Certainty Equivalent of Returns ($) per Acre for Varying Risk Aversion and Correlated Damages – Individual Regions

	$0.00/ton CO_2e			$0.10/ton CO_2e			$1.00/ton CO_2e		
RA[a] (λ)	***Coast***	***Piedmont***	***Upland***	***Coast***	***Piedmont***	***Upland***	***Coast***	***Piedmont***	***Upland***
0.000	1930	1724	1699	2033	1816	1808	3039	2771	2929
0.001	1733	1611	1682	1829	1699	1790	2712	2572	2899
0.005	946	1158	1616	1012	1229	1722	1407	1778	2778
0.025	-2989	-1104	1287	-3071	-1117	1378	-5118	-2193	2177

Tables 14 and 15 present the variance-covariance of returns with and without correlated damages for SCPL and RAFL respectively. At lower carbon price the introduction of damage correlation leads to a decline in variance in all three regions for RAFL and SCPL because damages have a tendency to move together. Lower damage in one or more regions implies that the damage in other regions declines as well leading to a decline in variance of returns. At higher carbon price the variance of returns increases in the coast for both RAFL and SCPL and in the piedmont for SCPL.

Table 14: SCPL: Variance-Covariance of Net Present Value of Returns for Correlated and Uncorrelated Damages ($/Acre)

Scenario	$0.10/ton CO2e/year			$1.00/ton CO2e/year		
	Uncorrelated Damages			Uncorrelated Damages		
Region	**Coast**	**Piedmont**	**Upland**	**Coast**	**Piedmont**	**Upland**
Coast	427,637	15,849	6,095	5,067,504	826,598	187,105
Piedmont	15,849	240,034	7,894	826,598	2,384,408	193,767
Upland	6,095	7,894	53,831	187,105	193,767	631,129
	Correlated Damages			**Correlated Damages**		
	Coast	**Piedmont**	**Upland**	**Coast**	**Piedmont**	**Upland**
Coast	404,211	45,587	5,289	5,284,582	1,005,546	166,127
Piedmont	45,587	227,740	5,016	1,005,546	2,539,196	209,776
Upland	5,289	5,016	33,820	166,127	209,776	560,207
	Percentage Change [a]			**Percentage Change**		
	Coast	**Piedmont**	**Upland**	**Coast**	**Piedmont**	**Upland**
Coast	(-) 5.48	(+) 65.23	(-) 13.22	(+) 4.11	(+) 17.80	(-) 11.21
Piedmont	(+) 65.23	(-) 5.12	(-) 36.46	(+) 17.80	(+) 6.10	(+) 7.63
Upland	(-) 13.22	(-) 36.46	(-) 37.17	(-) 11.21	(+) 7.63	(-) 11.24

[a] The sign indicates the direction of change, (+) indicates increase and (-) indicated decrease

Table 15: RAFL: Variance-Covariance of Net Present Value of Returns for Correlated and Uncorrelated Damages ($/Acre)

Scenario	$0.10/ton CO2e/year			$1.00/ton CO2e/year		
	Uncorrelated Damages			Uncorrelated Damages		
Region	**Coast**	**Piedmont**	**Upland**	**Coast**	**Piedmont**	**Upland**
Coast	433,899	15,378	5,776	675,177	27,287	4,770
Piedmont	15,378	247,069	7,980	27,287	427,372	13,738
Upland	5,776	7,980	54,862	4,770	13,738	86,362
	Correlated Damages			**Correlated Damages**		
	Coast	**Piedmont**	**Upland**	**Coast**	**Piedmont**	**Upland**
Coast	408,325	45,853	5,232	652,550	66,561	7,386
Piedmont	45,853	234,664	4,963	66,561	397,085	18,385
Upland	5,232	4,963	34,333	7,386	18,385	60,097
	Percentage Change [a]			**Percentage Change**		
	Coast	**Piedmont**	**Upland**	**Coast**	**Piedmont**	**Upland**
Coast	(-) 5.89	(+) 66.46	(-) 9.41	(+) 3.35	(+) 59.00	(+) 35.42
Piedmont	(+) 66.46	(-) 5.02	(-) 37.81	(+) 59.00	(-) 7.09	(+) 25.27
Upland	(-) 9.14	(-) 37.81	(-) 37.42	(+) 35.42	(+) 25.27	(-) 30.41

[a] The sign indicates the direction of change, (+) indicates increase and (-) indicated decrease

Tables 16 and 17 present the land investment in acres and certainty equivalent of returns for varying risk aversion for SCPL and RAFL, respectively, for all carbon price scenarios with correlated damage proportions. Under both SCPL and RAFL and with zero and non-zero carbon prices, the land investment increases significantly for the upland and decreases marginally for the piedmont and coast (compare with Tables 10 and 11). Investment in low damage areas (Upland) increases with higher damage correlations due to a significant decline in estimated variance of returns in Upland (Tables 14 and 15) as compared to high damage areas (Coast and Piedmont).

Table 16: SCPL Simulation Results – Optimal Land Investment and Certainty Equivalent of Returns [a] with Correlated Damages

	\$0.00/ton CO_2e				\$0.10/ton CO_2e				\$1.00/ton CO_2e			
	W_0=\$500,000				W_0=\$500,000				W_0=\$500,000			
Risk Aversion Coefficient	***Coast (Acres)***	***Piedmont (Acres)***	***Upland (Acres)***	***Certainty Equivalent***	***Coast (Acres)***	***Piedmont (Acres)***	***Upland (Acres)***	***Certainty Equivalent***	***Coast (Acres)***	***Piedmont (Acres)***	***Upland (Acres)***	***Certainty Equivalent***
0.00025	7	12	100	102,362	7	12	106	115,934	1	4	32	167,851
0.00050	4	6	50	51,181	4	6	53	57,967	0	2	16	83,926
0.00075	2	4	33	34,121	2	4	35	38,645	0	1	10	55,950
0.00100	2	3	25	25,591	2	3	26	28,984	0	1	8	41,963
0.00150	1	2	17	17,060	1	2	18	19,322	0	1	5	27,975
0.00200	1	1	13	12,795	1	2	13	14,492		0	4	20,981
0.00300	1	1	8	8,530	1	1	9	9,661			3	13,988
0.00500		1	5	5,118		1	5	5,797			1	8,393
0.01000			3	2,559			3	2,898			1	4,196
0.01100			2	2,326			2	2,635				3,815
0.01250			2	2,047			2	2,319				3,357
0.01500			2	1,706			2	1,932				2,798
0.02500			1	1,024			1	1,159				1,679

[a] The mean and certainty equivalent for risk neutral decision maker is \$500,000. Variance for the risk neutral decision maker would depend on actual allocation of land among the three regions.

Table 17: RAFL Simulation Results – Optimal Land Investment and Certainty Equivalent of Returns with Correlated Damages

	\$0.00/ton CO_2e				**\$0.10/ton CO_2e**				**\$1.00/ton CO_2e**			
	W_0=\$500,000				**W_0=\$500,000**				**W_0=\$500,000**			
Risk Aversion Coefficient	***Coast (Acres)***	***Piedmont (Acres)***	***Upland (Acres)***	***Certainty Equivalent***	***Coast (Acres)***	***Piedmont (Acres)***	***Upland (Acres)***	***Certainty Equivalent***	***Coast (Acres)***	***Piedmont (Acres)***	***Upland (Acres)***	***Certainty Equivalent***
0.00025	7	12	100	102,362	7	12	102	110,870	7	8	94	160,503
0.00050	4	6	50	51,181	4	6	51	55,435	4	4	47	80,251
0.00075	2	4	33	34,121	2	4	34	36,957	2	3	31	53,501
0.00100	2	3	25	25,591	2	3	26	27,718	2	2	24	40,126
0.00150	1	2	17	17,060	1	2	17	18,478	1	1	16	26,750
0.00200	1	1	13	12,795	1	1	13	13,859	1	1	12	20,063
0.00300	1	1	8	8,530	1	1	9	9,239	1	1	8	13,375
0.00500		1	5	5,118	-	1	5	5,544	-	-	5	8,025
0.01000			3	2,559	-	-	3	2,772	-	-	2	4,013
0.01100			2	2,326	-	-	2	2,520	-	-	2	3,648
0.01250			2	2,047	-	-	2	2,217	-	-	2	3,210
0.01500			2	1,706	-	-	2	1,848	-	-	2	2,675
0.02500			1	1,024	-	-	1	1,109	-	-	1	1,605

Conclusion

Our results imply that landowners would receive high benefits from both types of carbon sequestration contracts: stock change accounting with proportional liability and rental approach with full liability. Under the SCPL the landowner receives a higher expected return for a given level of risk as compared to the RAFL approach, which can be seen from Tables 8 and 9. If the landowner has the choice of entering into a contract with stock change type accounting or the rental approach type accounting, then they should enter into the contract based on stock change accounting which provides higher expected returns. The higher expected NPV of returns under SCPL results in higher land prices, assuming that the expected NPV is capitalized into land prices. Higher prices would mean fewer acres can be purchased with the fixed investment budget. However, risk averse decision makers prefer to keep some idle wealth so higher prices would not have an impact on their decision. Investment in fewer acres under SCPL is driven by higher variance of returns as compared to RAFL.

If the landowner enters a carbon contract with stock change accounting or the rental approach, then the landowner should delay forest harvest for carbon prices higher than \$1.00/ ton CO_2 equivalents for RAFL and \$0.10/ ton CO_2 equivalents for SCPL. If policymakers desire to keep the forest un-harvested, they might favor the SCPL approach. Timber market economics might mitigate the incentives to delay harvest if timber prices are high, or if timber prices or harvest quantity decline with age beyond some point.

In terms of the overall cost of meeting carbon reductions under the Kyoto Protocol through purchase of land-based carbon offsets, the rental approach is less costly as compared to the stock change approach. Moreover, from Table 10 and Table 11 it can be seen that the risk averse investor's land investment is higher under the RAFL as compared to the SCPL for \$1.00/ton CO_2 equivalents/yr. RAFL thus provides an incentive to bring more land into forest plantations, at higher carbon prices, for the purpose of creating carbon offsets.

Our simulations reveal that the effect of hurricane risk on landowners' behavior depends on the variability of returns from carbon and timber and the ability of landowners to mitigate the losses from risk by diversifying the portfolio of land (region) investment. A risk averse landowner has the choice of choosing a level of 'acceptable risk' corresponding to a given level of expected return and variance by diversifying holdings over more regions. Availability of government cost-share programs for carbon sequestration projects in forestry might increase landowner participation in such projects, especially for risk averse landowners or small landowners who might not have a very high initial risk-free wealth for investing in land for carbon sequestration purposes. However, such cost-share subsidies might also result in higher land prices.

Our analysis here could be extended in several directions. Firstly, we assume damage to forests does not depend on forest age. Younger trees might have more strength to withstand damage from hurricanes and older trees might be more prone to breakage and damage. The model could be extended to incorporate a higher likelihood of damage to older forests. Secondly, we assume that the damage to forests is independent of the hurricane intensity, although the hurricane strike probabilities and damage proportions are generated randomly based on historical data. The model could be extended to incorporate the likelihood of hurricanes of different intensities for the study regions. Thirdly, it would be interesting to see the behavior of landowners and carbon offset buyers in a mixed liability scheme where both parties assume some proportional liability for damages to sequestered carbon from natural disasters like hurricanes. Finally, in our model land price is set by risk neutral bidders/landowners. An interesting extension would be to examine landowner behavior when land prices are set by risk averse or a mix of risk averse and risk neutral bidders.

Chapter IV

EFFECTS OF INSURANCE ON FOREST LANDOWNERS' INCENTIVES TO SEQUESTER AND TRADE CARBON UNDER UNCERTAINTY: IMPACT OF HURRICANES

Introduction

Carbon insurance against catastrophic risks offers a cost-efficient tool for spreading risks across large groups of people and recovering damage costs (Wong and Dutschke). The traditional problems of moral hazard and adverse selection, which are a result of asymmetric information, have limited applicability to hurricane insurance. The occurrence of specific hazards is easily identified by the insurer as by the insured landowner, and the potential losses are easier to assess on a region-by-region basis (Goodwin and Smith, p. 34).

Traditionally catastrophic risk insurance/aid in the U.S. has been offered as part of the multiple peril crop insurance program (Hueth and Furtan; Goodwin and Smith). In the U.S., catastrophic risk insurance involves government subsidization because catastrophic events like hurricanes or floods are correlated across regions (Duncan and Myers; Wong and Dutschke). This might lead to very large losses which a private insurer might not be able to recover through pooling risks faced by all landowners (Skees and Barnett; Duncan and Myers). Rainfall and hail crop insurance is offered by private insurance companies (Hueth and Furtan; Goodwin and Smith) because these risks are not correlated across regions. Specialized forestry insurance against losses from natural hazards is offered in a few countries such as New Zealand, Australia, Norway and Japan (Subak; Wong and Dutschke). Carbon insurance has not developed as a specialized risk management tool; however, the possibility of including land-based carbon offset trading under the Kyoto Protocol and the concerns over non-permanence of these offsets might lead insurance companies to offer competitive carbon insurance.

Certain firms such as SwissRe, MunichRe and ForestRe offer specialized risk mitigation tools for managing, compliance, and performance and delivery risk in GHG emissions markets. Some of the risk mitigation tools that are discussed include price risk protection, financial or physical settlement for non-delivery, weather risk management tools, delivery guarantee insurance and catastrophe bonds (Walker, Croson and Kunreuther). Common barriers to involvement of private financial companies in the GHG trading markets may be the uncertainty with regard to a formal market/platform for interested parties, a complex and tedious process for registering emissions reductions to be considered as valid credits which can be traded, lack of infrastructure for setting up GHG trading markets, and identifying whether a project is 'additional' (UNEP; Rolfe). There have been discussions regarding the Canadian government's proposal to establish an insurance mechanism' to guarantee, for a limited time, the validity of credits from carbon sink projects given the issue of non-permanence (Boshyk). Purchasing insurance for certified emissions reductions under the Clean Development Mechanism has also been proposed in UNFCCC's report on the definitions and modalities for including afforestation and reforestation project activities (UNFCCC).

This chapter will focus on answering the following questions:

- Does purchasing private insurance impact the optimal portfolio strategies of a risk averse landowner?
- Does purchasing private insurance encourage greater landowner participation, especially for risk averse landowners?
- How do diversification of forestry investment locations and buying insurance compare in terms of reducing landowners' risk from forestry investments for sequestration and timber purposes?

The main objective of this chapter is to assess effects of insurance on optimal portfolios of carbon projects for landowners engaged in GHG mitigation and trade in the forestry sector in hurricane prone regions of United States.

Research objectives are to:

1. Develop a conceptual model to analyze a forest landowner's/investor's "portfolio of location choice strategies" given the risk of carbon loss from hurricanes and availability of insurance for risk mitigation.
2. Estimate the empirical model of the forest landowner to illustrate the impact of hurricane risk, insurance and landowner's risk aversion on the landowner's "portfolio of location choice strategies".

The availability of reinsurance or the opportunity of spreading risk across uncorrelated risks might affect the supply of insurance, but would not affect insurance demand. We focus is on the demand for insurance by landowners and we assume that insurers are willing to offer actuarially fair insurance against loss of carbon offsets due to hurricanes. For this paper it is assumed that insurers are able to use the law of large numbers for eliminating the aggregate risk by insuring different types of catastrophic risks across different geographic regions or by reinsuring with diversified reinsurance firms (Duncan and Myers). Our framework is a step towards analyzing how risk management strategies can increase landowners' incentives to participate in carbon markets.

Basic Optimization Model

The forest plantation model developed in Chapter 3 is applied in the state of South Carolina which is divided into three major sub-regions – coastal, piedmont and upland (Figure 1). The accounting and liability mechanisms or carbon payment schemes considered are Stock Change approach with Proportional landowner Liability (SCPL) and Rental Approach of accounting with Full landowner Liability (RAFL).

The problem of the landowner under both the SCPL and RAFL approaches is to choose the optimal amount of land acquired in each of the regions, A_i (i= 1, 2, 3), at the beginning of the project period, i.e., at t =1, for the purpose of creating carbon offsets and selling timber so as to maximize expected utility. The model in Chapter 3 is extended to incorporate the insurance model presented in the next section.

Insurance Model

Our insurance model is based on design of the existing crop insurance program in the U.S. (Barnett and Coble; Goodwin and Smith; Hueth and Furtan). It is assumed that only losses of yield of carbon offsets resulting from hurricane events are insured. The level of yield coverage and the level of price coverage are chosen by the landowner. It is assumed that insurance yield is based on an estimate of the potential yield of carbon offsets per acre. We assume that φ_d is the coverage level chosen by the landowner and $0 \le \varphi_d \le 1$. The carbon offsets are insured at the market price for these offsets.

The yield guarantee per acre is equal to the estimated yield multiplied by the level of coverage chosen by the landowner. If landowner's actual yield is equal to or greater than the yield guarantee, no indemnity is paid. If the yield per acre is less than yield guarantee, the indemnity paid is equal to the yield difference times the indemnity price, which is market price of carbon offsets. Where $\varphi_d R_{it}$ is the yield guarantee and $R_{it} - y_{it} D_{it}$ is the actual yield per acre and p is the market price. Indemnity under SCPL is defined as follows:

$$I_i = p\left[\varphi_d R_{it} - (R_{it} - y_{it} D_{it})\right](T - t) \ge 0 \qquad \ldots (24)$$

Indemnity under RAFL is defined as follows:

$$I_i = p\left[\varphi_d B_{it} - (B_{it} - y_{it} M_{it})\right] \ge 0 \qquad \ldots (25)$$

Where, $\varphi_d B_{it}$ is the yield guarantee and $B_{it} - y_{it} M_{it}$ is the actual yield per acre. The indemnity is constrained to be greater than or equal to zero for both payment schemes.

It is assumed that the insurance company is able to offer actuarially fair insurance such that the insurance premium that a landowner pays in a given period *t* is equal to the expected value of indemnity payment. Insurance premium under both SCPL and RAFL is given by:

$$\pi_i = \sum_{j=1}^{m} \mu_i^{\,j} I_i \qquad \ldots (26)$$

where, π_i is the insurance premium per unit of coverage level in region *i*, and $\overset{j}{\mu}_{it}$ is the probability of j^{th} hurricane in region *i*. The net present value of income for a landowner who buys insurance in region *i* is given by:

$$Q_i' = Q_i + \left(\sum_{t=1}^{T} \frac{I_i - \pi_i}{(1+r)^t} \right) A_i \qquad \ldots (27)$$

It is assumed that the landowner chooses 100% insurance coverage level, $\varphi_d = 1$.

Simulation and Optimization Model

@Risk software offered by Palisade Corporation is used to generate simulation data on expected returns from forestry and carbon offset sales under different accounting and liability scenarios with and without insurance coverage using Monte Carlo simulations. We ran 1000 iterations to generate data on net present value of returns in coast, piedmont and upland under different carbon price scenarios. The risk profiles for hurricane risk and corresponding damages to forest stand are specified using @Risk. The distributions of net returns under insurance and no insurance scenarios over the planning horizon are derived from the simulations. These distributions are used to estimate the variance-covariance matrix of returns between the three regions, the expected net present value of returns, the optimal rotation ages in three regions and land prices. These data are input into a Quadratic Programming model, which is solved using General Algebraic Modeling System (GAMS), to determine the optimal amount of land that the landowner will invest in the three regions under various scenarios. Equation (11), the objective function, is maximized to determine the optimal amount of land A_i that the landowner invests in at the beginning of the planning horizon subject to the land constraint equation

(18). The optimal amount of land is estimated for different levels of risk aversion for the forest landowner by parametrically changing the risk aversion coefficient λ. A range of risk aversion parameters is considered between zero for a risk neutral landowner to 80 for a highly risk averse landowner (McCarl and Spreen). These data are then used to develop the mean-variance efficient frontier for the landowner.

Results and Discussion

Certainty Equivalent of Net Present Value

Tables 18 and 19 present the certainty equivalent (CE) of net present value (NPV) of returns over a 100-year planning horizon for SCPL and RAFL, respectively, for different levels of risk aversion under two carbon price scenarios. Actuarially fair insurance is assumed such that premium is equal to expected value of indemnities paid over the planning horizon based on the simulation data. With risk neutrality, the CE of NPV with and without insurance should be very close because premiums were set equal to expected indemnities. The CE of the $ 1.00 carbon price under SCPL (Table 18) and risk neutrality are somewhat higher without insurance. This difference is due to discounting. Premiums tended to occur relatively sooner in the project lifetime compared to indemnities and were thus discounted somewhat less. As the level of risk aversion increases, the CE of NPV becomes negative indicating that the risk premium becomes larger than the mean of returns due to higher variance of returns. T he risk premium increases at a faster rate for the coast as compared to piedmont and upland because of higher variance of returns in the coast.

Under both SCPL and RAFL the CE declines at a much lower rate when insurance is purchased, indicating a decline in variance. However, the CE is declining with increasing risk aversion even with insurance because timber losses are not insured. If we assume the risk free rate of time preference to be equal to zero the NPV under insurance and no insurance scenarios for SCPL and RAFL under all carbon price scenarios are unchanged.

Table 18: SCPL: Certainty Equivalent of Net Present Value of Returns (Per Acre) for Varying Risk Aversion – Individual Regions

	$0.10/ton CO2e/year						$1.00/ton CO2e/year					
	No Insurance			100% Insurance			No Insurance			100% Insurance		
RA[a] (λ)	***Coast***	***Piedmont***	***Upland***	***Coast***	***Piedmont***	***Upland***	***Coast***	***Piedmont***	***Upland***	***Coast***	***Piedmont***	***Upland***
0.000	2050	1838	1837	2042	1835	1837	6653	8252	9405	6368	7869	9313
0.001	1848	1725	1820	1846	1724	1820	4010	6983	9125	5466	7313	9239
0.005	1039	1269	1752	1066	1279	1754	-6559	1904	8005	1860	5090	8944
0.025	-3003	-1008	1414	-2838	-946	1425	-59405	-23487	2403	-16170	-6028	7466

[a] Risk aversion coefficient

Table 19: RAFL: Certainty Equivalent of Net Present Value of Returns (Per Acre) for Varying Risk Aversion – Individual Regions

	$0.10/ton CO2e/year						$1.00/ton CO2e/year					
	No Insurance			100% Insurance			No Insurance			100% Insurance		
RA[a] (λ)	***Coast***	***Piedmont***	***Upland***	***Coast***	***Piedmont***	***Upland***	***Coast***	***Piedmont***	***Upland***	***Coast***	***Piedmont***	***Upland***
0.000	2033	1816	1808	2032	1816	1808	3039	2771	2929	3030	2762	2927
0.001	1829	1699	1790	1829	1699	1790	2712	2572	2899	2716	2570	2898
0.005	1012	1229	1722	1015	1231	1722	1407	1778	2778	1460	1801	2783
0.025	-3071	-1117	1378	-3052	-1110	1380	-5118	-2193	2177	-4820	-2041	2206

[a] Risk aversion coefficient

Variance of Net Present Value

Tables 20 and 21 present the variance-covariance of net present value of returns in all three regions for SCPL and RAFL, respectively, and the percentage decline in variance-covariance after insurance is purchased. For SCPL with \$0.10/ton CO_2 equivalents/year, the variance in the coastal region decreases by 3.4%, in the piedmont by 2.3% and in the upland by 2.8% when the landowner buys insurance. For \$1.00/ton CO_2 equivalents/year the variance in the coastal region decreases by 66%, in the piedmont by 56% and in the upland by 74% when the landowner buys insurance. For RAFL with \$0.10/tonCO_2 equivalents/year the variance in the coastal region decreases by 0.4%, in the piedmont by 0.3% and in the upland by 0.4% when the landowner buys insurance. For \$1.00/tonCO_2 equivalents/year the variance in the coastal region decreases by 4%, in the piedmont by 3% and in the upland by 4% when the landowner buys insurance. The decline in variance under RAFL is less significant than the decline in variance under SCPL because uninsured timber returns form a larger proportion of total returns under RAFL.

Table 20: SCPL: Variance-Covariance of Net Present Value of Returns ($/Acre)

Scenario	$0.10/ton CO2e/year			$1.00/ton CO2e/year		
	No Insurance			No Insurance		
Region	Coast	Piedmont	Upland	Coast	Piedmont	Upland
Coast	404,211	45,587	5,289	5,284,582	1,005,546	166,127
Piedmont	45,587	227,740	5,016	1,005,546	2,539,196	209,776
Upland	5,289	5,016	33,820	166,127	209,776	560,207
	100% Insurance			100% Insurance		
	Coast	Piedmont	Upland	Coast	Piedmont	Upland
Coast	390,390	43,925	5,184	1,803,018	161,284	57,749
Piedmont	43,925	222,451	4,582	161,284	1,111,754	57,691
Upland	5,184	4,582	32,883	57,749	57,691	147,788
	Percentage Decline			Percentage Decline		
	Coast	Piedmont	Upland	Coast	Piedmont	Upland
Coast	3.42	3.64	1.99	65.88	83.96	65.24
Piedmont	3.64	2.32	8.65	83.96	56.22	72.50
Upland	1.99	8.65	2.77	65.24	72.50	73.62

Table 21: RAFL: Variance-Covariance of Net Present Value of Returns ($/Acre)

Scenario	$0.10/ton CO2e/year			$1.00/ton CO2e/year		
	No Insurance			No Insurance		
Region	Coast	Piedmont	Upland	Coast	Piedmont	Upland
Coast	408,325	45,853	5,232	652,550	66,561	7,386
Piedmont	45,853	234,664	4,963	66,561	397,085	18,385
Upland	5,232	4,963	34,333	7,386	18,385	60,097
	100% Insurance			100% Insurance		
	Coast	Piedmont	Upland	Coast	Piedmont	Upland
Coast	406,759	45,613	5,226	628,012	62,998	7,190
Piedmont	45,613	234,008	4,915	62,998	384,273	17,580
Upland	5,226	4,915	34,210	7,190	17,580	57,746
	Percentage Decline			Percentage Decline		
	Coast	Piedmont	Upland	Coast	Piedmont	Upland
Coast	0.38	0.52	0.13	3.76	5.35	2.66
Piedmont	0.52	0.28	0.96	5.35	3.23	4.38
Upland	0.13	0.96	0.36	2.66	4.38	3.91

Proportion of Returns and Variance by Timber and Carbon

Tables 22, 23, 24 and 25 present NPV and variance of NPV from timber and carbon offset returns as a proportion of total NPV and variance of NPV with \$0.10/ton CO2e/year and \$0.10/ton CO2e/year for SCPL and RAFL, respectively. At lower carbon price of \$0.10/ton CO2e/year, NPV of returns from timber form a much greater proportion, around 97%, of the total returns under both SCPL and RAFL with and without insurance as compared to returns from carbon offsets in all regions. Similarly, the variance of NPV of timber returns also forms a very large proportion of total variance of NPV of returns from both timber and carbon offsets. The variance of NPV of timber returns forms a marginally higher proportion of total variance when returns from carbon offsets are insured in all regions.

Table 22: SCPL – Proportion of Expected NPV and Variance of NPV by Timber and Carbon for \$0.10/ton CO2e/year

	Timber			**Carbon**		
Region	**Coast**	**Piedmont**	**Upland**	**Coast**	**Piedmont**	**Upland**
	No Insurance					
NPV of Returns	0.95	0.95	0.93	0.05	0.05	0.07
Variance of NPV	0.97	0.98	0.97	0.03	0.02	0.03
	100% Insurance					
NPV of Returns	0.96	0.96	0.93	0.04	0.04	0.07
Variance of NPV	0.99	0.99	0.99	0.01	0.01	0.01

Table 23: RAFL – Proportion of Expected NPV and Variance of NPV by Timber and Carbon for $0.10/ton CO2e/year

	Timber			Carbon		
Region	**Coast**	**Piedmont**	**Upland**	**Coast**	**Piedmont**	**Upland**
	No Insurance					
NPV of Returns	0.96	0.96	0.94	0.04	0.04	0.06
Variance of NPV	0.97	0.97	0.96	0.03	0.03	0.04
	100% Insurance					
NPV of Returns	0.96	0.96	0.94	0.04	0.04	0.06
Variance of NPV	0.99	0.98	0.98	0.01	0.02	0.02

At higher carbon price of $1.00/ton CO2e/year, NPV of returns from carbon offsets form a much greater proportion, almost 100%, of the total returns under SCPL both with and without insurance in all regions (Table 24). Similarly, the variance of NPV of carbon offset returns also forms a very large proportion of total variance of NPV of returns from both timber and carbon offsets. Availability of insurance does not have an impact on the proportions of NPV and variance of NPV for timber and carbon offsets because returns form carbon offsets form a very high proportion of total returns even without insurance.

Under RAFL NPV of returns from timber form around 60% - 70% of the total returns both with and without insurance as compared to returns from carbon offsets in all regions (Table 25). The variance of NPV of timber returns forms between 48% - 63% of the total returns without insurance in all regions. The variance of NPV of timber returns forms a marginally higher proportion of total variance when returns from carbon offsets are insured in all regions.

Table 24: SCPL – Proportion of Expected NPV and Variance of NPV by Timber and Carbon for $1.00/ton CO2e/year

	Timber			Carbon		
Region	**Coast**	**Piedmont**	**Upland**	**Coast**	**Piedmont**	**Upland**
	No Insurance					
NPV of Returns	0.01	0.01	0.01	0.99	0.99	0.99
Variance of NPV	0.01	0.01	0.01	0.99	0.99	0.99
	100% Insurance					
NPV of Returns	0.02	0.02	0.01	0.98	0.98	0.99
Variance of NPV	0.01	0.01	0.01	0.99	0.99	0.99

Table 25: RAFL – Proportion of Expected NPV and Variance of NPV by Timber and Carbon for $1.00/ton CO2e/year

	Timber			Carbon		
Region	**Coast**	**Piedmont**	**Upland**	**Coast**	**Piedmont**	**Upland**
	No Insurance					
NPV of Returns	0.70	0.59	0.60	0.30	0.41	0.40
Variance of NPV	0.63	0.48	0.57	0.37	0.52	0.43
	100% Insurance					
NPV of Returns	0.70	0.59	0.60	0.30	0.41	0.40
Variance of NPV	0.65	0.50	0.59	0.35	0.50	0.41

Optimal Land Investment

Risk averse landowner diversifies into all three regions with the highest level of investment in the upland followed by piedmont and then coast with and without insurance (Tables 26 and 27). Because the upland has the lowest hurricane strike probability and lowest variance of returns amongst all three regions and since the CE of NPV in upland declines less as the level of risk aversion increases (Table 18) compared to the other two regions, the landowner is motivated to shift a major portion of his/her investment to the upland. When the landowner has the option of buying insurance in all three regions the risk averse landowner diversifies into all three regions because not all risk has been insured. Timber losses which are not insured are still a source of risk for investment and a cause for large variance in returns. The overall amount of land investment for the risk averse landowner increases with the availability of insurance because the variance of net present value of returns declines.

The overall trend in land investment for \$1.00/ton CO_2 equivalents for SCPL (Table 28) are similar to those for carbon price of \$0.10/ton CO_2 equivalents (Table 26); although the overall amount of land investment for the risk averse landowner with and without insurance is marginally lower as compared to the scenario with carbon price of \$0.10/ton CO_2 equivalents due to higher variance-covariance of returns. Land prices are higher with \$1.00/ton CO_2 equivalents; however the wealth constraint is not binding because risk averse landowners prefer to keep a proportion of the fixed wealth idle. The trends in results for land investment for RAFL are similar to those for SCPL (Tables 27 and 29).

Table 26: SCPL - Optimal Land Investment and Certainty Equivalent of Returns for $0.10/ton CO2e/year

Risk Aversion Coefficient	***Coast (Acres)***	***Piedmont (Acres)***	***Upland (Acres)***	***Certainty Equivalent***	***Coast (Acres)***	***Piedmont (Acres)***	***Upland (Acres)***	***Certainty Equivalent***
	No Insurance				**100% Insurance**			
0.00025	7	12	106	115,934	8	13	108	119,341
0.00050	4	6	53	57,967	4	7	54	59,670
0.00075	2	4	35	38,645	3	4	36	39,781
0.00100	2	3	26	28,984	2	3	27	29,836
0.00150	1	2	18	19,322	1	2	18	19,890
0.00200	1	2	13	14,492	1	2	14	14,917
0.00300	1	1	9	9,661	1	1	9	9,945
0.00500		1	5	5,797	-	1	6	5,968
0.01000			3	2,898	-	-	3	2,987
0.01100			2	2,635	-	-	3	2,715
0.01250			2	2,319	-	-	2	2,390
0.01500			2	1,932	-	-	2	1,991
0.02500			1	1,159	-	-	1	1,195

Table 27: RAFL - Optimal Land Investment and Certainty Equivalent of Returns for $0.10/ton CO2e/year

Risk Aversion Coefficient	***Coast (Acres)***	***Piedmont (Acres)***	***Upland (Acres)***	***Certainty Equivalent***	***Coast (Acres)***	***Piedmont (Acres)***	***Upland (Acres)***	***Certainty Equivalent***
	No Insurance				**100% Insurance**			
0.00025	7	12	102	110,870	7	12	103	111,273
0.00050	4	6	51	55,435	4	6	51	55,637
0.00075	2	4	34	36,957	2	4	34	37,091
0.00100	2	3	26	27,718	2	3	26	27,818
0.00150	1	2	17	18,478	1	2	17	18,546
0.00200	1	1	13	13,859	1	1	13	13,909
0.00300	1	1	9	9,239	1	1	9	9,273
0.00500	-	1	5	5,544	-	1	6	5,564
0.01000	-	-	3	2,772	-	-	3	2,782
0.01100	-	-	2	2,520	-	-	3	2,529
0.01250	-	-	2	2,217	-	-	2	2,225
0.01500	-	-	2	1,848	-	-	2	1,855
0.02500	-	-	1	1,109	-	-	1	1,113

Table 28: SCPL - Optimal Land Investment and Certainty Equivalent of Returns for $1.00/ton CO2e/year

Risk Aversion Coefficient	***Coast (Acres)***	***Piedmont (Acres)***	***Upland (Acres)***	***Certainty Equivalent***	***Coast (Acres)***	***Piedmont (Acres)***	***Upland (Acres)***	***Certainty Equivalent***
	No Insurance				**100% Insurance**			
0.00025	1	4	32	167,851	1	3	50	396,872
0.00050	0	2	16	83,926	1	3	50	293,744
0.00075	0	1	10	55,950	1	2	41	202,014
0.00100	0	1	8	41,963	1	2	31	151,510
0.00150	0	1	5	27,975	-	1	20	101,007
0.00200	-	0	4	20,981	-	1	15	75,755
0.00300	-	-	3	13,988	-	1	10	50,503
0.00500	-	-	1	8,393	-	-	6	30,302
0.01000	-	-	1	4,196	-	-	3	15,151
0.01100	-	-	-	3,815	-	-	3	13,774
0.01250	-	-	-	3,357	-	-	2	12,121
0.01500	-	-	-	2,798	-	-	2	10,101
0.02500	-	-	-	1,679	-	-	1	6,060

Table 29: RAFL - Optimal Land Investment and Certainty Equivalent of Returns for $1.00/ton CO2e/year

Risk Aversion Coefficient	***Coast (Acres)***	***Piedmont (Acres)***	***Upland (Acres)***	***Certainty Equivalent***	***Coast (Acres)***	***Piedmont (Acres)***	***Upland (Acres)***	***Certainty Equivalent***
	No Insurance				**100% Insurance**			
0.00025	7	8	94	160,503	8	9	98	166,662
0.00050	4	4	47	80,251	4	4	49	83,331
0.00075	2	3	31	53,501	3	3	33	55,554
0.00100	2	2	24	40,126	2	2	24	41,666
0.00150	1	1	16	26,750	1	1	16	27,777
0.00200	1	1	12	20,063	1	1	12	20,833
0.00300	1	1	8	13,375	1	1	8	13,889
0.00500	-	-	5	8,025	-	-	5	8,333
0.01000	-	-	2	4,013	-	-	2	4,167
0.01100	-	-	2	3,648	-	-	2	3,788
0.01250	-	-	2	3,210	-	-	2	3,333
0.01500	-	-	2	2,675	-	-	2	2,778
0.02500	-	-	1	1,605	-	-	1	1,667

Mean-Variance Frontier

Figure 6 presents the mean variance (EV) frontier for the positive levels of risk aversion with and without carbon insurance for the SCPL accounting approach with both carbon price scenarios. Increasing the carbon price from \$0.10 to \$1.00/ton CO_2 equivalents shifts the EV frontier upward and to the left. The returns to the land have become more favorable, meaning that at any given level of risk (variance) the expected returns have increased. Availability of carbon insurance also shifts the EV frontier further to the left although the effect is more noticeable for the \$1.00/ton CO_2 equivalents price. The returns to land have become less variable, meaning at any given level of expected returns the variance of returns has decreased. Figure 7 presents the EV frontier for RAFL which shows results similar to those for SCPL, though the changes are less significant as compared to SCPL.

Figure 6: SCPL - EV Frontier Over Positive Risk Aversion

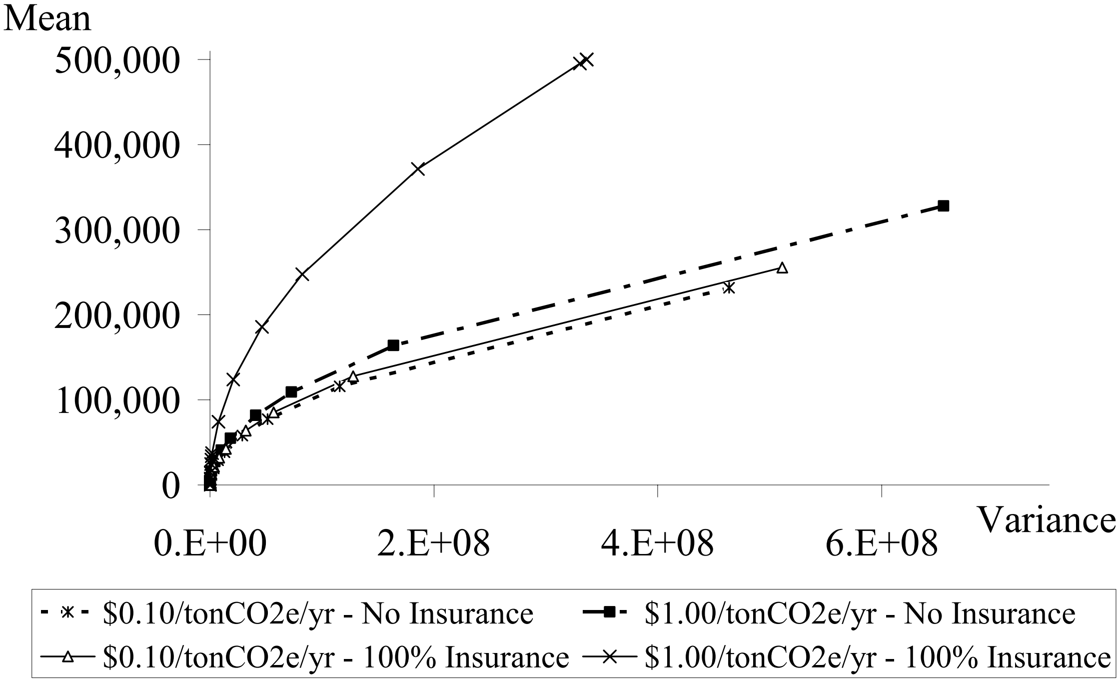
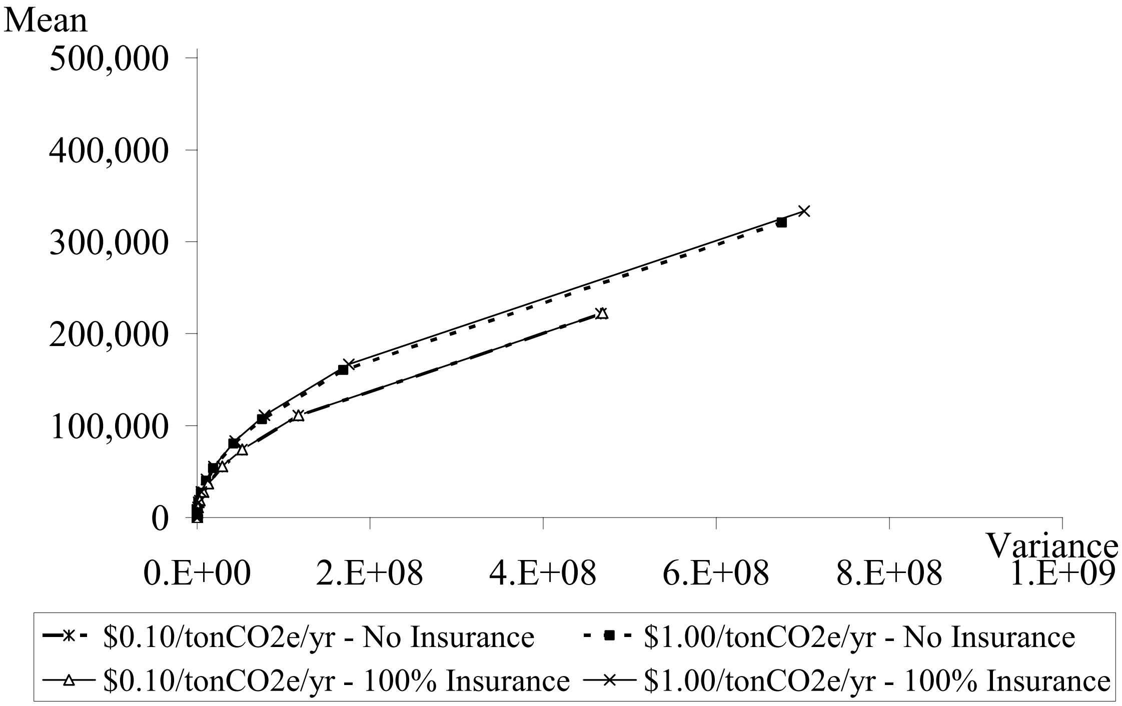


Figure 7: RAFL - EV Frontier Over Positive Risk Aversion



Diversification vs. Insurance

Tables 30, 31 and 32 represent the land investment in acres and certainty equivalent of returns for varying levels of risk aversion for the coast, piedmont and upland, respectively, under SCPL. Tables 33, 34 and 35 present the same data for RAFL. These tables present the results for the landowner when the landowner does not have the option of diversifying into different regions and invests in only one region.

Table 30: SCPL: Coast - Optimal Land Investment and Certainty Equivalent of Returns

	\$0.00/ton CO_2e		**\$0.10/ton CO_2e**				**\$1.00/ton CO_2e**			
	No Insurance		**No Insurance**		**100% Insurance**		**No Insurance**		**100% Insurance**	
Risk Aversion Coefficient	***Investment***	***Certainty Equivalent***	***Investment***	***Certainty Equivalent***	***Investment***	***Certainty Equivalent***	***Investment***	***Certainty Equivalent***	***Investment***	***Certainty Equivalent***
0.00025	10	9,465	10	10,397	10	10,681	2	8,376	7	22,491
0.00050	5	4,733	5	5,198	5	5,340	1	4,188	4	11,245
0.00075	3	3,155	3	3,466	3	3,561	1	2,792	2	7,497
0.00100	2	2,366	3	2,599	3	2,671	1	2,094	2	5,623
0.00150	2	1,578	2	1,733	2	1,780		1,396	1	3,748
0.00200	1	1,183	1	1,300	1	1,335		1,047	1	2,811
0.00300	1	789	1	866	1	890		698	1	1,874
0.00500	-	473	1	520	1	534		418	-	1,125
0.01000	-	237	-	260	-	267		210	-	562
0.01100	-	215	-	236	-	243		191	-	511
0.01250	-	188	-	208	-	213		167	-	450
0.01500	-	158	-	173	-	178		139	-	375
0.02500	-	94	-	104	-	106		83	-	225

Table 31: SCPL: Piedmont - Optimal Land Investment and Certainty Equivalent of Returns

	\$0.00/ton CO_2e		**\$0.10/ton CO_2e**				**\$1.00/ton CO_2e**			
	No Insurance		**No Insurance**		**100% Insurance**		**No Insurance**		**100% Insurance**	
Risk Aversion Coefficient	***Investment***	***Certainty Equivalent***	***Investment***	***Certainty Equivalent***	***Investment***	***Certainty Equivalent***	***Investment***	***Certainty Equivalent***	***Investment***	***Certainty Equivalent***
0.00025	15	13,136	16	14,834	16	15,137	7	26,817	14	55,697
0.00050	8	6,569	8	7,417	8	7,569	3	13,403	7	27,848
0.00075	5	4,379	5	4,945	5	5,045	2	8,939	4	18,566
0.00100	4	3,284	4	3,708	4	3,784	2	6,705	4	13,924
0.00150	3	2,189	3	2,472	3	2,523	1	4,469	2	9,283
0.00200	2	1,642	2	1,854	2	1,892	1	3,352	2	6,962
0.00300	1	1,095	1	1,236	1	1,262	1	2,235	1	4,641
0.00500	1	657	1	742	1	757		1,341	1	2,785
0.01000		328		371		379		671	-	1,392
0.01100		298		337		344		609		1,266
0.01250		262		296		302		537		1,114
0.01500		219		247		253		447		928
0.02500		132		149		151		268		557

Table 32: SCPL: Upland - Optimal Land Investment and Certainty Equivalent of Returns

	$0.00/ton CO_2e		**$0.10/ton CO_2e**				**$1.00/ton CO_2e**			
	No Insurance		**No Insurance**		**100% Insurance**		**No Insurance**		**100% Insurance**	
Risk Aversion Coefficient	***Investment***	***Certainty Equivalent***	***Investment***	***Certainty Equivalent***	***Investment***	***Certainty Equivalent***	***Investment***	***Certainty Equivalent***	***Investment***	***Certainty Equivalent***
0.00025	103	87,539	109	99,780	112	102,624	34	157,896	52	393,502
0.00050	51	43,770	54	49,890	56	51,312	17	78,948	52	287,005
0.00075	34	29,180	36	33,260	37	34,208	11	52,632	45	195,622
0.00100	26	21,885	27	24,945	28	25,656	8	39,474	34	146,717
0.00150	17	14,590	18	16,630	19	17,104	5	26,316	22	97,811
0.00200	13	10,942	14	12,473	14	12,828	4	19,737	17	73,358
0.00300	9	7,295	9	8,315	9	8,552	3	13,154	11	48,906
0.00500	5	4,377	5	4,989	6	5,131	2	7,895	7	29,343
0.01000	3	2,188	3	2,495	3	2,566	1	3,948	3	14,672
0.01100	2	1,990	2	2,268	3	2,332	1	3,588	3	13,338
0.01250	2	1,751	2	1,996	2	2,052	1	3,157	3	11,737
0.01500	2	1,459	2	1,663	2	1,710	1	2,631	2	9,781
0.02500	1	876	1	998	1	1,026	-	1,579	1	5,869

Table 33: RAFL: Coast - Optimal Land Investment and Certainty Equivalent of Returns

	$0.00/ton CO_2e		$0.10/ton CO_2e				$1.00/ton CO_2e			
	No Insurance		No Insurance		100% Insurance		No Insurance		100% Insurance	
Risk Aversion Coefficient	***Investment***	***Certainty Equivalent***	***Investment***	***Certainty Equivalent***	***Investment***	***Certainty Equivalent***	***Investment***	***Certainty Equivalent***	***Investment***	***Certainty Equivalent***
0.00025	10	9,465	10	10,122	10	10,151	9	14,153	10	14,619
0.00050	5	4,733	5	5,061	5	5,076	5	7,076	5	7,309
0.00075	3	3,155	3	3,374	3	3,384	3	4,718	3	4,873
0.00100	2	2,366	2	2,531	2	2,538	2	3,538	2	3,655
0.00150	2	1,578	2	1,687	2	1,692	2	2,359	2	2,436
0.00200	1	1,183	1	1,265	1	1,269	1	1,769	1	1,827
0.00300	1	789	1	844	1	846	1	1,179	1	1,218
0.00500		473		506	1	508		708	-	731
0.01000		237		253		254		354	-	365
0.01100		215		230		231		321		332
0.01250		188		202		203		283		293
0.01500		158		169		169		236		243
0.02500		94		101		102		141		146

Table 34: RAFL: Piedmont- Optimal Land Investment and Certainty Equivalent of Returns

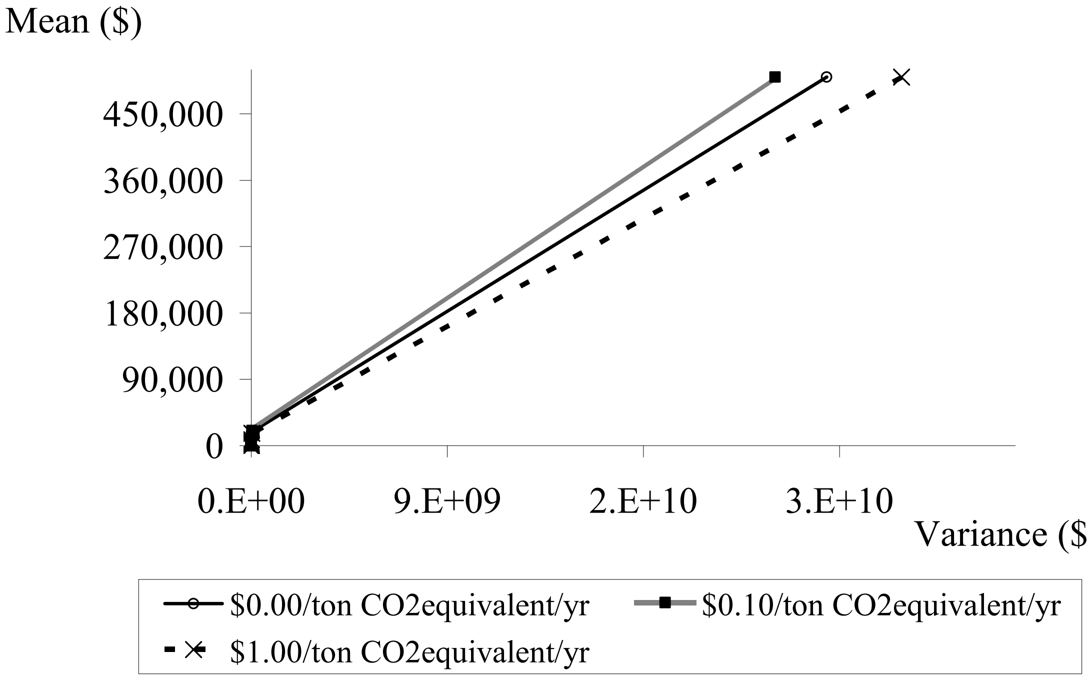
	$0.00/ton CO_2e		**$0.10/ton CO_2e**				**$1.00/ton CO_2e**			
	No Insurance		**No Insurance**		**100% Insurance**		**No Insurance**		**100% Insurance**	
Risk Aversion Coefficient	***Investment***	***Certainty Equivalent***	***Investment***	***Certainty Equivalent***	***Investment***	***Certainty Equivalent***	***Investment***	***Certainty Equivalent***	***Investment***	***Certainty Equivalent***
0.00025	15	13,136	15	14,054	16	14,093	14	19,337	14	19,852
0.00050	8	6,569	8	7,027	8	7,046	7	9,669	7	9,926
0.00075	5	4,379	5	4,685	5	4,698	5	6,446	5	6,617
0.00100	4	3,284	4	3,513	4	3,523	3	4,834	4	4,963
0.00150	3	2,189	3	2,342	3	2,349	2	3,223	2	3,309
0.00200	2	1,642	2	1,757	2	1,762	2	2,417	2	2,482
0.00300	1	1,095	1	1,171	1	1,174	1	1,611	1	1,654
0.00500	1	657	1	703	1	705	1	967	1	993
0.01000		328		351		352		483		496
0.01100		298		319		321		439		451
0.01250		262		281		282		387		397
0.01500		219		234		235		322		331
0.02500		132		141		141		193		198

Table 35: RAFL: Upland - Optimal Land Investment and Certainty Equivalent of Returns

	\$0.00/ton CO$_2$e		**\$0.10/ton CO$_2$e**				**\$1.00/ton CO$_2$e**			
	No Insurance		**No Insurance**		**100% Insurance**		**No Insurance**		**100% Insurance**	
Risk Aversion Coefficient	***Investment***	***Certainty Equivalent***	***Investment***	***Certainty Equivalent***	***Investment***	***Certainty Equivalent***	***Investment***	***Certainty Equivalent***	***Investment***	***Certainty Equivalent***
0.00025	103	87,539	105	95,211	106	95,553	97	142,753	101	148,362
0.00050	51	43,770	53	47,605	53	47,776	49	71,377	51	74,181
0.00075	34	29,180	35	31,737	35	31,851	32	47,584	34	49,454
0.00100	26	21,885	26	23,803	26	23,888	24	35,688	25	37,091
0.00150	17	14,590	18	15,868	18	15,925	16	23,792	17	24,727
0.00200	13	10,942	13	11,901	13	11,944	12	17,844	13	18,545
0.00300	9	7,295	9	7,934	9	7,963	8	11,896	8	12,364
0.00500	5	4,377	5	4,761	5	4,778	5	7,138	5	7,418
0.01000	3	2,188	3	2,380	3	2,389	2	3,569	3	3,709
0.01100	2	1,990	2	2,164	2	2,172	2	3,244	2	3,372
0.01250	2	1,751	2	1,904	2	1,911	2	2,855	2	2,967
0.01500	2	1,459	2	1,587	2	1,593	2	2,379	2	2,473
0.02500	1	876	1	952	1	956	1	1,428	2	1,484

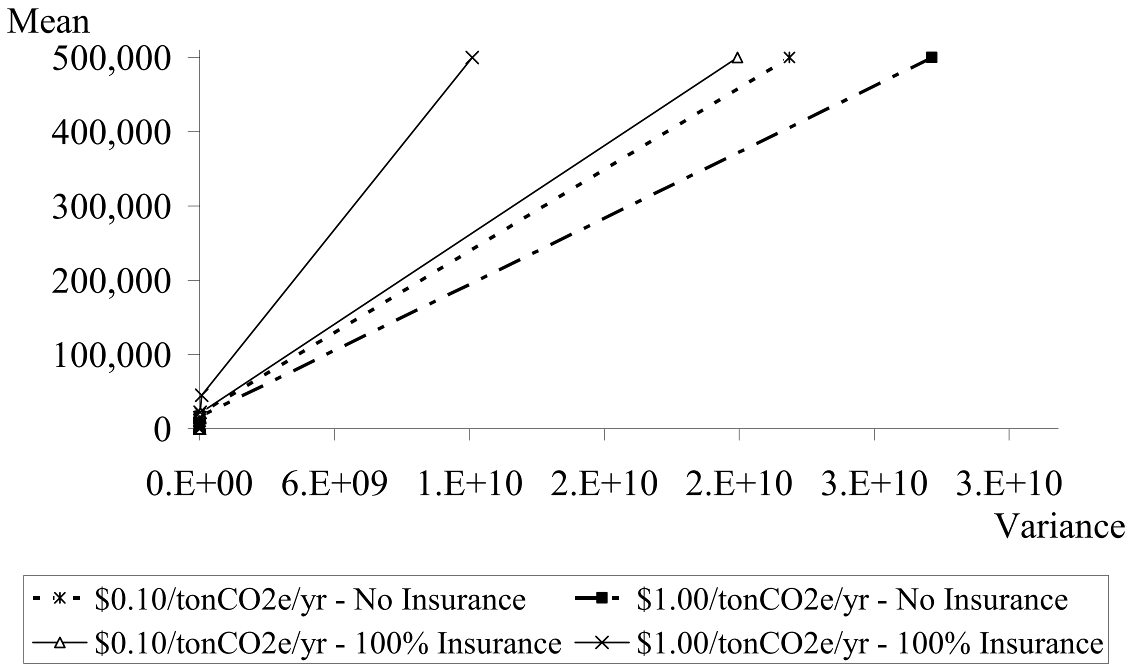
Results for the coast in Table 30 and Figure 8 suggest that without insurance the CE with \$1.00/ton CO_2 equivalents is the lowest due to very high variance of returns. Buying insurance increases both the land investment and CE for moderately risk averse decision makers at non-zero carbon prices.

Figure 8: SCPL - EV Frontier for Coast with Varying Carbon Prices and No Insurance



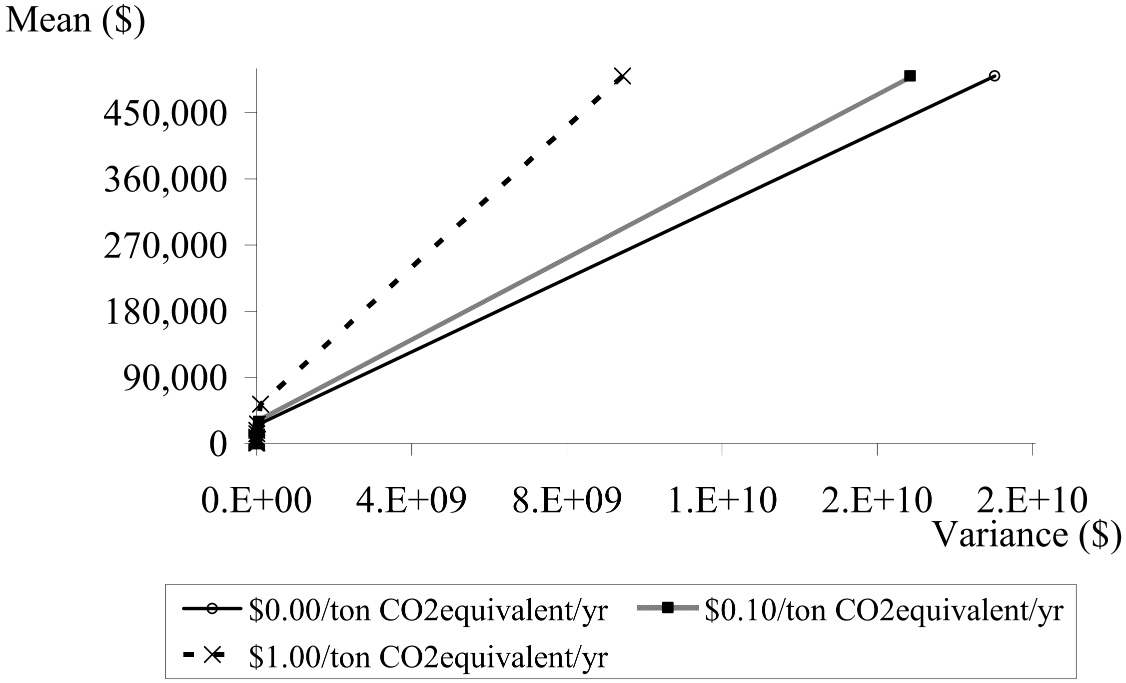
Availability of insurance reduces the variability of returns, which can be seen in Figure 9. The landowner benefits by being on a higher EV-frontier, which implies the same level of expected returns can be earned with lower variance. The EV-frontier with \$1.00/ton CO_2 equivalents/ year now dominates \$0.10/ton CO_2 equivalents with insurance, whereas this was not the case without insurance.

Figure 9: SCPL - EV Frontier for Coast with and without Insurance



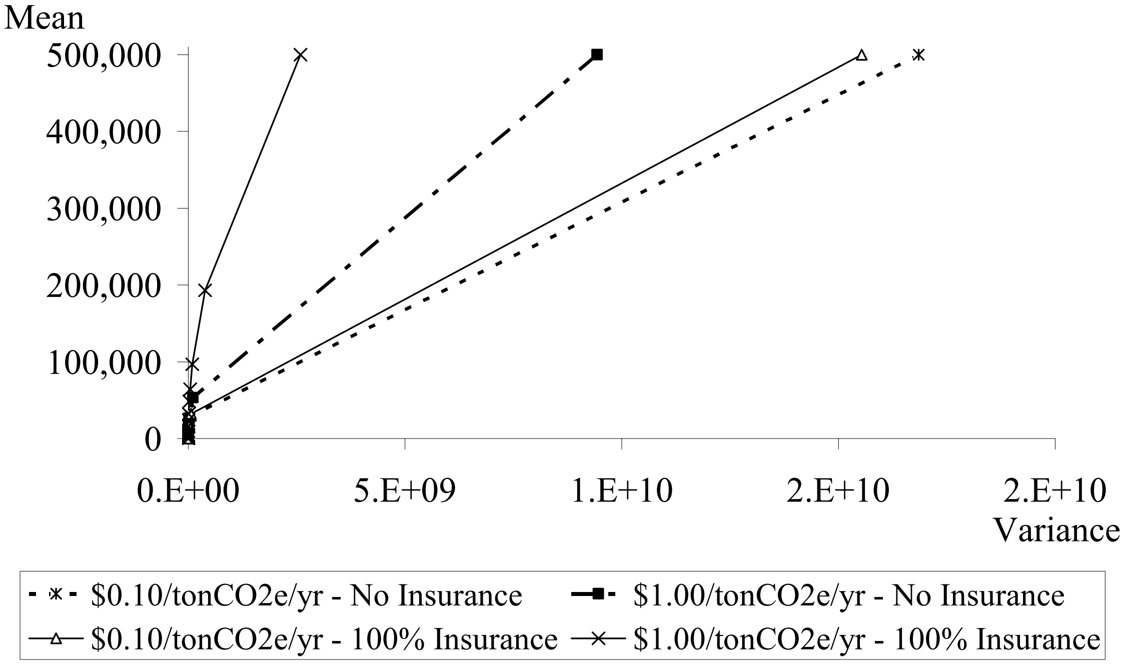
Results for the piedmont under SCPL in Table 31 and Figure 10 suggest that without insurance the CE with $1.00/ton CO_2 equivalents is the highest because higher expected returns outweigh the increase in variance of returns.

Figure 10: SCPL - EV Frontier for Piedmont with Varying Carbon Prices



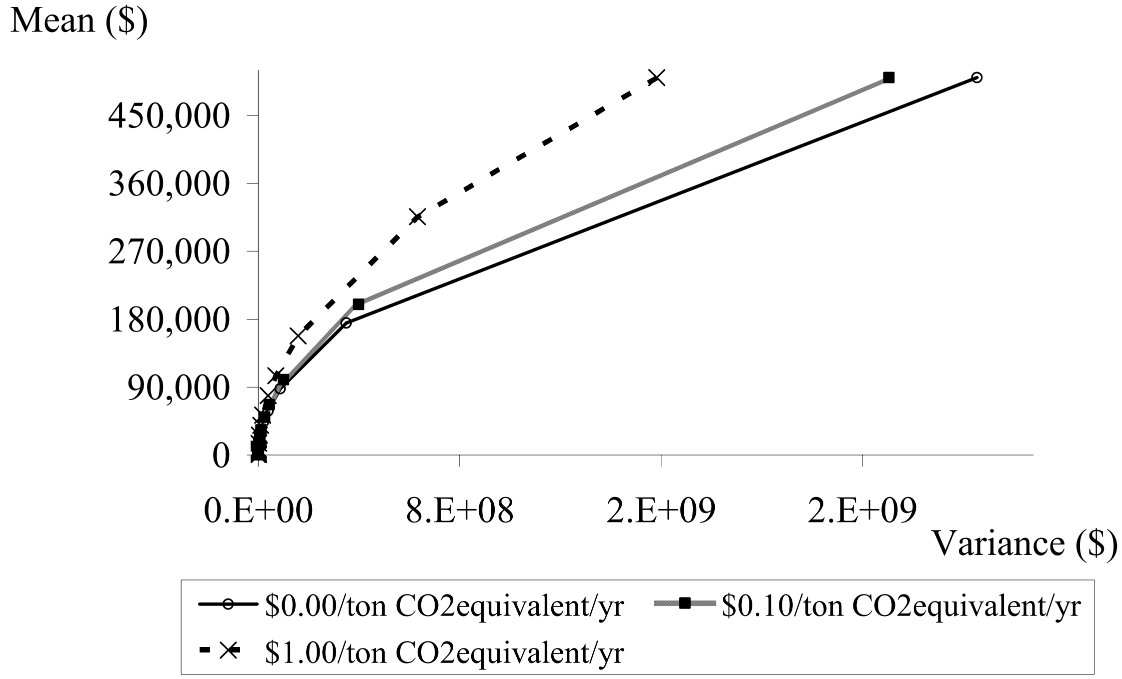
Buying insurance increases both the land investment and CE for moderately risk averse decision makers at non-zero carbon prices. Availability of insurance reduces the variability of returns, which can be seen in Figure 11 which shows that the landowner benefits by being on a higher EV-frontier which implies the same level of expected returns can be earned with lower variance.

Figure 11: SCPL - EV Frontier for Piedmont with and without Insurance



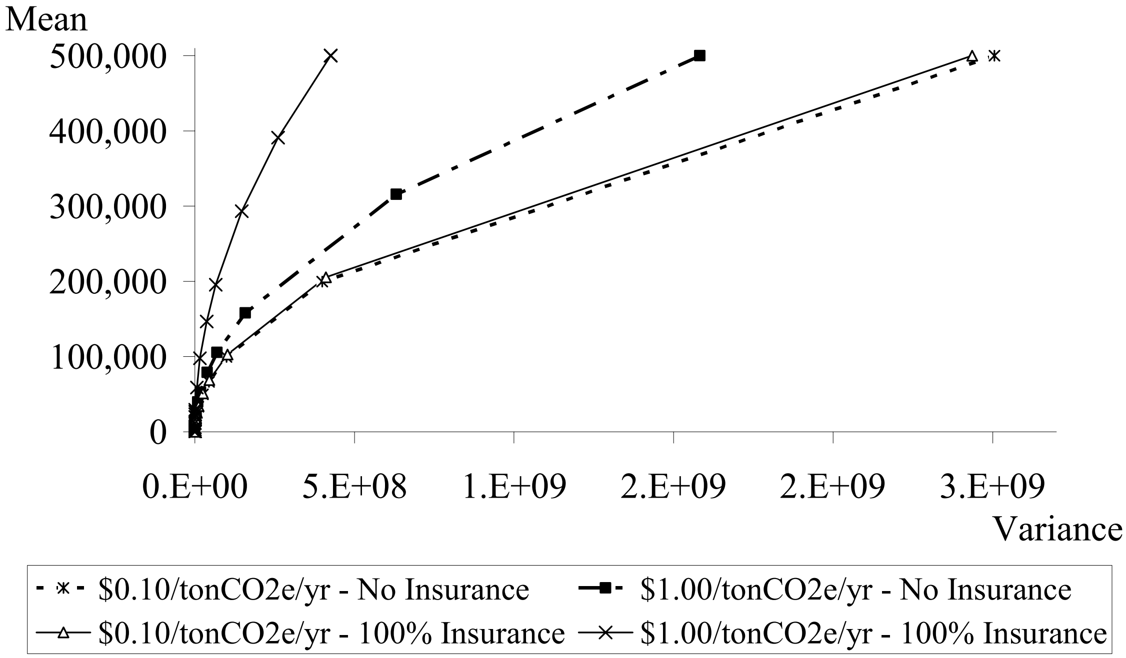
Results for the upland under SCPL in Table 32 and Figure 12 suggests that without insurance the CE with $1.00/ton CO_2 equivalents is the highest because higher expected returns outweigh the increase in variance of returns.

Figure 12: SCPL - EV Frontier for Upland with Varying Carbon Prices



Buying insurance increases both the land investment and CE for risk-neutral decision makers at non-zero carbon prices. Availability of insurance reduces the variability of returns, which can be seen in Figure 13 which shows that the landowner benefits by being on a higher EV-frontier.

Figure 13: SCPL - EV Frontier for Upland with and without Insurance



Results for the coast under RAFL in Table 33 and Figure 14, the piedmont in Table 34 and Figure 15 and the upland in Table 35 and Figure 16 suggest that without insurance the CE with \$1.00/ton CO_2 equivalents is the highest because higher expected returns outweigh the increase in variance of returns. Buying insurance increases both the land investment and CE for moderately risk averse decision makers at non-zero carbon prices. Availability of insurance reduces the variability of returns and the landowner benefits by being on a higher EV-frontier.

Figure 14: RAFL - EV Frontier for Coast with and without Insurance

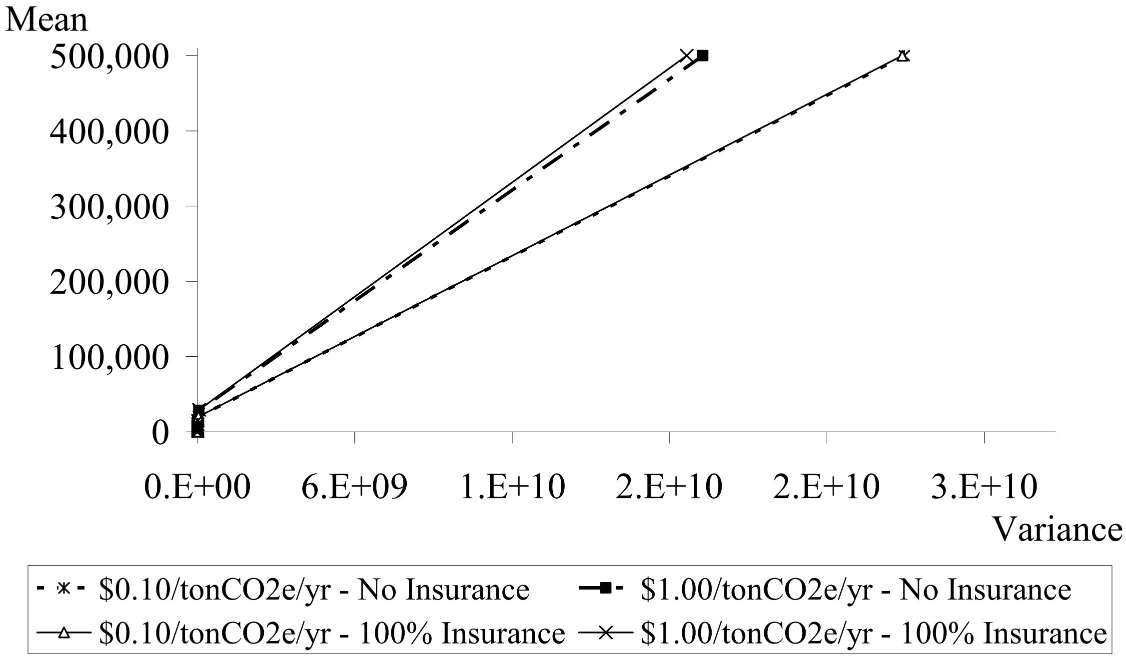


Figure 15: RAFL - EV Frontier for Piedmont with and without Insurance

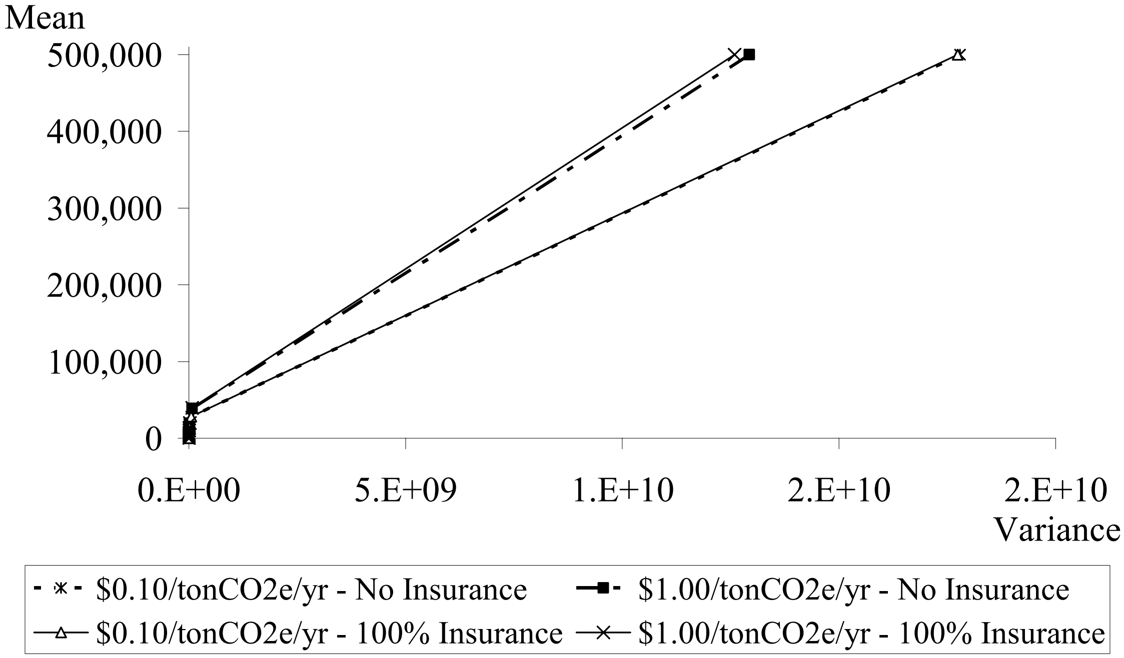
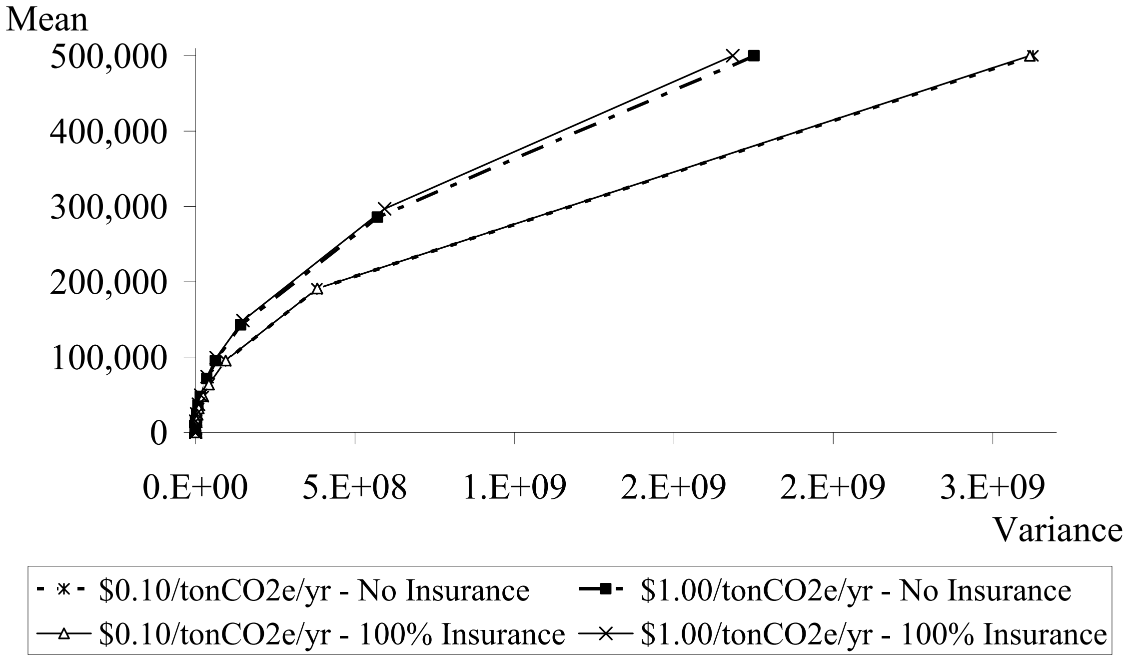


Figure 16: RAFL - EV Frontier for Upland with and without Insurance



Figures 17, 18, 19 and 20 represent the results in terms of E-V-frontiers under SCPL and RAFL with diversification and insurance. The figures show that insurance has a role to play over and above diversification in terms of increasing landowner benefits. In Figures 17 and 19, for $0.10/ton CO_2 equivalents and SCPL and RAFL, respectively, the E-V frontier with diversification and insurance is the highest and leftmost, followed by E-V frontier with diversification (All regions) without insurance, followed by E-V frontiers without diversification i.e., for individual regions both with and without insurance. Figures 18 and 20 present the results in terms of E-V frontiers for $1.00/ton CO_2 equivalents under SCPL and RAFL with diversification and insurance. The E-V frontier with diversification and insurance is the highest and leftmost, followed by E-V frontier for upland with insurance, followed by E-V frontier with diversification (All regions) without insurance, followed by EV frontiers without diversification i.e., for coast and piedmont both with and without insurance.

Figure 17: SCPL: $0.10/tonCO2e/yr - Diversification and Insurance

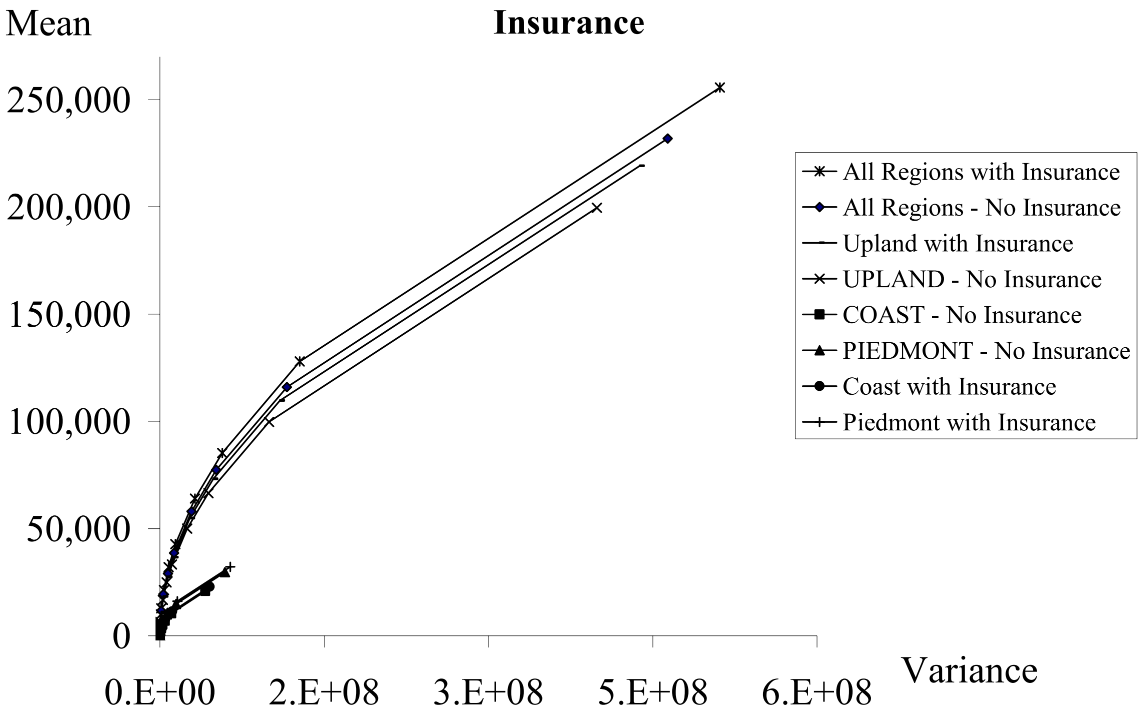


Figure 18: SCPL: $1.00/tonCO2e/yr - Diversification and Insurance

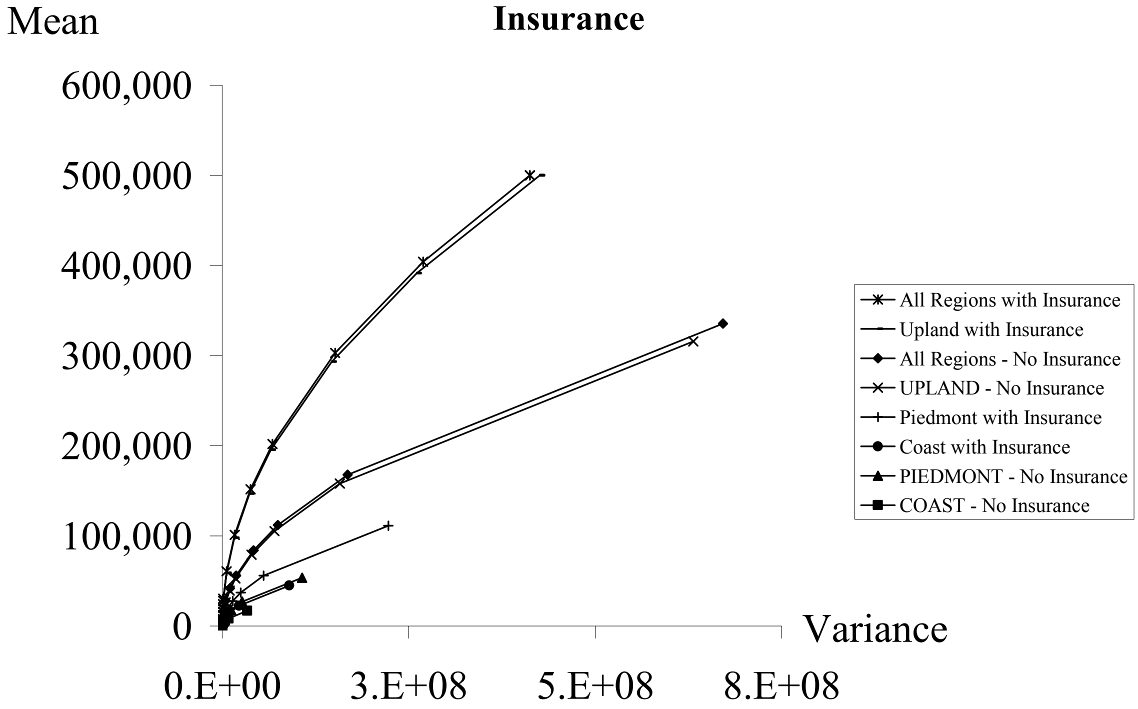


Figure 19: RAFL: $0.10/tonCO2e/yr - Diversification and Insurance

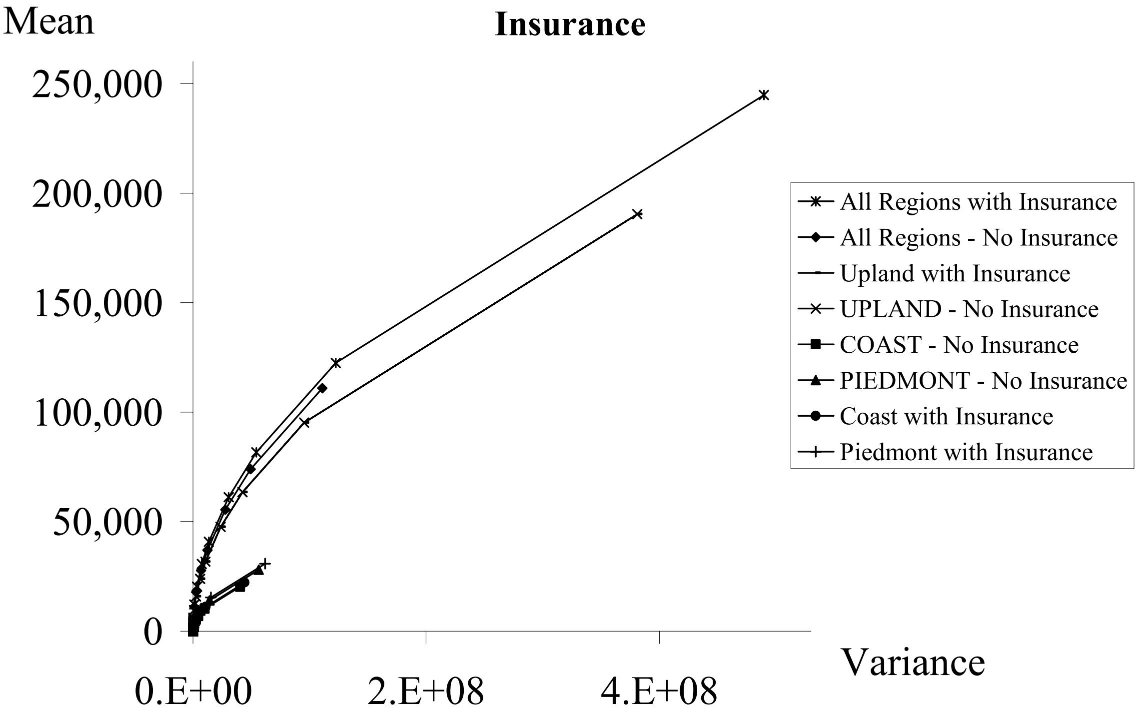
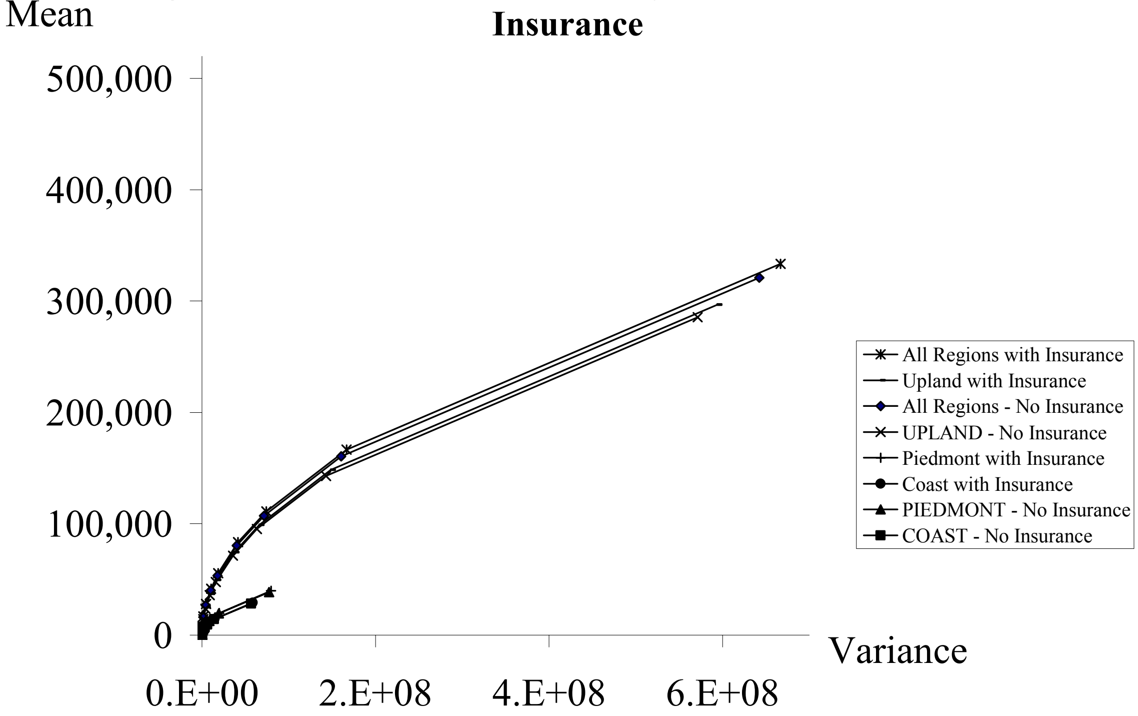


Figure 20: RAFL: $1.00/tonCO2e/yr - Diversification and Insurance



Conclusion

Purchasing insurance under both carbon accounting scenarios, SCPL and RAFL, and different carbon price scenarios has some impact on the optimal portfolio strategies of risk averse landowners. The availability of carbon insurance encourages higher land investment and thus encourages greater landowner participation under both accounting and price scenarios. From Tables 26, 27, 28, and 29 it can be seen that the risk averse investor's land investment is higher with insurance under both carbon prices of $0.10 and $1.00/ton CO_2 equivalents/year. Without insurance, the investor's land investment is higher under $0.10 than $1.00/ton CO_2 equivalents/year due to the lower variance of returns at lower carbon price. Insurance has a role to play over and above diversification of forestry investment locations in terms of reducing landowners' risks (variance) from forestry investments for sequestration and timber purposes, even when timber losses are not insured.

The simulation results reveal that the effect of hurricane risk on landowners' behavior depends on the variability of returns from carbon and timber and the ability of landowners to mitigate the losses from risk by diversifying the portfolio of land (region) investment or their ability to transfer the risk to an insurance company. A risk averse landowner has the choice of choosing a level of 'acceptable risk' corresponding to a given level of expected return and variance by diversifying holdings over more regions or by purchasing insurance for carbon losses. Availability of carbon insurance has the potential for providing incentive for higher land investment; which will be especially beneficial in bringing marginal or waste land into forest plantation use for the purpose of carbon sequestration. Carbon insurance thus provides an incentive, by transferring risk, over and above the incentive provided by diversification, for investing in land for the purpose of carbon sequestration and timber.

It would be interesting to see how the behavior of landowners is affected by the availability of timber insurance along with carbon insurance. Insuring timber losses from hurricanes in addition to insuring carbon losses will provide added incentives to invest in land in regions with high biomass growth rates which result in higher carbon and timber returns.

Chapter V

CONCLUSION

Uncertainty and risk are central to environmental management problems. Given the various sources of risks and uncertainty associated with carbon offset trading markets there is need to assess the impact of these risks at the time of carbon offsets market establishment and/or project development. These risks might affect buyers and sellers alike and may have an impact on their decisions to participate in GHG trading markets.

This research had three main objectives. The first objective was to identify various sources of risk and uncertainty in greenhouse gas offset trading markets. Presence of risk and uncertainty might be a deterrent for both buyers and sellers of GHG offsets to participate in trading. The second objective was to assess the effect of risk of carbon loss due to natural disasters on forest landowners' incentive for purchasing land for new forest plantations for the purpose of creating carbon offsets and timber. The third objective was to analyze how insuring loss of carbon due to natural disasters might affect landowner incentives for creating and trading carbon offsets. Two carbon accounting scenarios were considered, stock change accounting with proportional landowner liability (SCPL) and rental accounting with full landowner liability (RAFL).

The first objective was achieved by carrying out a literature review. Based on the reviewed literature risks associated with carbon offsets policy can be classified into three major categories: institutional/policy, project level and measurement risks. Institutional/policy risks are related to uncertainties surrounding the future policy decisions and the institutional arrangements established. Policy/institutional risks relate to baselines, monitoring/enforcement, and leakage. Baseline estimates are necessary to calculate the net carbon reduction of a program or project. Monitoring/enforcement risk is associated with the regulators' ability to detect whether the promised carbon sequestration activities are undertaken. Leakage occurs when carbon sequestration at one site encourages increase in carbon emissions on some other site. Project risk refers to non-performance of a carbon sequestration project in terms of not achieving the requisite target of carbon sequestration. Project risk includes physical risk and financial risk. Physical risks are associated with unexpected carbon emissions due to natural hazards or events such as fire, or hurricanes or changes in the rate of sequestration, which depend on weather and pests. Landowners will not participate in carbon sequestration programs if they expect to incur financial losses by participating. Measurement risk arises because it is difficult to measure actual rates of carbon sequestered due to spatial and temporal heterogeneity of carbon present in agricultural and forest production.

The second and third objectives were achieved with a simulation model designed using @Risk and a quadratic programming model designed using GAMS. The simulation results suggested that landowners would receive high benefits from either type of carbon sequestration contracts considered for this research: stock change accounting with proportional liability (SCPL) and rental approach with full liability (RAFL). Under the SCPL the landowner receives a higher expected return for a given level of risk as compared to the RAFL approach. In terms of the overall cost of meeting carbon reductions under the Kyoto Protocol through purchase of land-based carbon offset offsets, the rental approach is less costly as compared to the stock change approach.

If the landowner enters a carbon contract with stock change accounting or the rental approach then the landowner should delay forest harvest for carbon prices higher than \$1.00/ ton CO_2 equivalents for RAFL and \$0.10/ ton CO_2 equivalents for SCPL. If policymakers desire to keep the forest un-harvested, they can favor SCPL over RAFL at lower carbon prices. Timber market economics might mitigate the incentives to delay harvest if timber prices are high, or if timber prices or harvest quantity decline with age beyond some point.

The effect of hurricane risk on landowners' behavior depends on the variability of returns from carbon and timber and the ability of landowners to mitigate the losses from risk by diversifying the portfolio of land (region) investment or their ability to transfer the risk to an insurance company. A risk averse landowner has the choice of choosing a level of 'acceptable risk' corresponding to a given level of expected return and variance by diversifying holdings over more regions or by purchasing insurance for carbon losses. The simulation results indicate that risk averse landowner diversifies into all three regions and highest investment in land is undertaken in the upland which is the region with lowest hurricane risk and also the lowest rate of sequestration.

For achieving the third objective, the model under second objective was extended to incorporate indemnity and premium payments. The simulation results suggest that availability of carbon insurance has the potential for providing incentive for higher land investment; which will be especially beneficial in bringing marginal or waste land into forest plantation use for the purpose of carbon sequestration. Overall, diversification provides higher net present values, helps to spread risk and allows the landowner to be on a higher EV-Frontier as compared to if the landowner invests only in one region.

Availability of insurance increases the certainty equivalent of returns for the risk averse landowner as a result of decline in the variance of returns. Moreover, insurance provides an incentive for higher land investment over and above the incentive provided by diversification by transferring the risk of carbon loss to the insurance company, and allowing the landowner to be on higher E-V Frontier when the landowner has the option of investing in all three regions. However, landowner diversifies into all three regions, despite availability of carbon insurance in all regions because timber losses remain uninsured. Availability of government cost-share programs for carbon sequestration projects in forestry might increase landowner participation in such projects, especially for risk averse landowners or small landowners who might not have a very high initial risk-free wealth for investing in land for carbon sequestration purposes. However, such cost-share subsidies might also result in higher land prices.

Our analysis here could be extended in several directions. Firstly, we assume damage to forests does not depend on forest age. Younger trees might have more strength to withstand damage from hurricanes and older trees might be more prone to breakage and damage. The model could be extended to incorporate a higher likelihood of damage to younger forests. Secondly, we assume that the damage to forests is independent of the hurricane intensity, although the hurricane strike probabilities and damage proportions are generated randomly based on historical data. The model could be extended to incorporate the likelihood of hurricanes of different intensities for the study regions. Thirdly, it would be interesting to see the behavior of landowners and carbon offset buyers in a mixed liability scheme where both parties assume some proportional liability for damages to sequestered carbon from natural disasters like hurricanes. Fourthly, in our model land price is set by risk neutral bidders/landowners. An interesting extension would be to examine landowner behavior when land prices are set by risk averse or a mix of risk averse and risk neutral bidders. Finally, it would be interesting to see how the behavior of landowners is affected by the availability of timber insurance along with carbon insurance. Insuring timber losses from hurricanes in addition to insuring carbon losses will provide added incentives to invest in land in regions with high biomass growth rates which result in higher carbon and timber returns.

REFERENCES

Best Fit Palisade Corporation. http://www.palisade.com/html/bestfit.asp.

@Risk4.5 Palisade Corporation. http://www.palisade.com/html/risk.asp.

Amacher, G. S., R. J. Brazee, and T. A. Thomson. “The Effect of Forest Productivity Taxes on Timber Stand Investment and Rotation Length.” *Forest Science* 37 (4) (1991)**:** 1099-1118.

Antle, J., S. Capalbo, S. Mooney, E. Elliot, and K. Paustian. “A Comparative Examination of the Efficiency of Sequestering Carbon in US Agricultural Soils.” *American Journal of Alternative Agriculture* 17(3) (2002):109-115.

Barnett, B.J., and K.H. Coble. “Understanding Crop Insurance Principles: A Primer for Farm Leaders” Mississippi Agricultural and Forestry Experiment Station Bulletin 1087, 1999.

Birdsey, R.A. *Carbon Storage and Accumulation in United States Forest Ecosystems.* USDA Forest Service, General Technical Report WO-59, Washington, DC, 1992.

Birdsey, R. A. “Carbon Storage for Major Forest Types and Regions in the Conterminous United States.” *Forests and Global Change Volume 2, Forest Management Opportunities for Mitigating Carbon Emissions.* R. Neil Sampson and Dwight Hair eds., pp. 1- 25. American Forests, Washington DC, 1996.

Boshyk, A. *Climate Change and Investment Risk: Best Practices for Canadian Pension Funds and Institutional Investors.* Environment Canada. A report on the Climate Change and Investment Risk Workshop, March 11, 2004, Toronto.

Breshears D. D., and C. D. Allen. “The importance of rapid, disturbance- induced losses in carbon management and sequestration.” *Global Ecology and Biogeography Letters* 11 (2002): 1–5.

Brown, S. “Guidelines for Inventorying and Monitoring Carbon Offsets in Forest-Based Projects.” Winrock International, Arlington, VA. Prepared for the World Bank, (1999).

Brown, S. “Measuring Carbon in Forests: Current Status and Future Challenges.” *Environmental Pollution* 116 (2002): 363-372.

Brown, S. “Review of Methodologies Relating to the Issue of Permanence for LULUCF Projects.” Cooperative Agreement between Winrock International and the EPA ID# CR 827293-01-0, Product 11, November (2002).

Brown, S., M. H. P. Hall, F. Ruiz, a. Flamenco, B. DeJong, L. Auckland, O. Masera, and D. Shoch. “Land Use and Forestry Projects that Abate Greenhouse Gas Emissions: Baselines and Additionality.” Winrock International, US AID-supported Research. 2002.

Cairns, R.D., and P. Lasserre. "Reinforcing Economic Incentives for Carbon Credits for Forests" *Forest Policy and Economics* 6 (2004): 321-328.

Chang, S. J. “A Simple Production Function Model for Variable Density Growth and Yield Modeling.” *Canadian Journal of Forest Research* 14 (1984): 783-788.

Chiang, Alpha C. *Fundamental Methods of Mathematical Economics*, 3rd edition, McGraw-Hill Book Company, 1984.

Chomitz, K.M. "Evaluating carbon offsets from forestry and energy projects: How do they compare?" World Bank Policy Research Working Paper 2315. World Bank Development Research Group, Washington DC, USA, 25p, (2000). (http://www.worldbank.org/research)

Chomitz, K. M., and F. Lecocq. "Temporary Sequestration Credits: An Instrument for Carbon Bears." World Bank, Working Paper No. 3181, Washington, DC, December 24, 2003.

Cohen, Sheldon M. "Carbon-based Conservation Strategies in Latin America: An Innovative Tool for Financing Environmental Conservation" *The Geneva Papers* 27 (2002): 255-267.

Croson, David C.. and Howard Kunreuther. "Customizing Reinsurance and Cat Bonds for Natural Hazard Risks", Working Paper 99-05-15, Wharton Risk Management and Decision Processes Center, University of Pennsylvania, Philadelphia , PA, (1999).

Dales, J. H. *Pollution, Property & Prices: an Essay in Policy Making and Economics*. University of Toronto Press, 1968.

de Figueiredo, M.A., H. J.Herzog, and D. M. Reiner. "Framing the Long-Term Liability Issue for Geologic Carbon Storage in the United States." *Mitigation and Adaptation Strategies for Global Change,* 2005.

Duncan, J., and R.J. Myers. "Crop Insurance under Catastrophic Risk." *Journal of Agricultural Economics* 82(4) (2000): 824-855.

Enzinger, S., and C. Jeffs. "Economics of Forests as Carbon Sinks: An Australian Perspective." *Journal of Forest Economics,* 6 (3) (2000): 227-249.

Faber, M., R. Manstetten, and J. L. R. Proops. “Human kind and the environment: An anatomy of surprise and ignorance.” *Environmental Values* 1 (1992): 217-241.

Goodnow Jr., R. W. “The Effects of Ice Damage on Management Decisions for Loblolly Pine Plantations located in the Piedmont Region of Virginia” Thesis, Master of Science in Forestry, Department of Forestry, Virginia Polytechnic Institute and State University, February 2002.

Goodwin, Barry K., and Vincent H. Smith. *The Economics of Crop Insurance and Disaster Aid.* Washington: American Enterprise Institute, 1995.

Gray, W. M. “Strong association between West African rainfall and U.S. landfall of intense hurricanes.” *Science* 249 (1990): 1251-1256.

Gupta, Shreekant. “Incentive-based Approaches for Mitigating Greenhouse Gas Emissions: Issues and Prospects for India” Report No. 86, MIT Joint Program on the Science and Policy of Global Change, Cambridge, MA. 2002.

Haight, R. G., W. D. Smith, and T. J. Straka. “Hurricanes and the Economics of Loblolly Pine Plantations.” *Forest Science* 41 (1995): 675-688.

Harkin, Z., and G.Q. Bull. “An international forest carbon accounting framework: A system for managing, measuring, reporting and trading forest carbon from an operational to an international scale.” IEA Bioenergy Task 25/38 International Workshop, Canberra, Australia, March 29-31, 2001.

Herzog, H., K. Caldeira, and J. Reilly, "An Issue of Permanence: Assessing the Effectiveness of Temporary Carbon Storage," *Climatic Change* 59 (3) 2003: 293-310.

Hueth, Darrell L., and William H. Furtan. *Economics of Agricultural Crop Insurance: Theory and Evidence.* Kluwer Academic Publishers, 1994.

Intergovernmental Panel on Climate Change (IPCC). *Greenhouse Gas Inventory Reference Manual*, Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories, Vol. 3 Paris, France, 1997.

Leining, C. R. "The eligibility of land-use, land-use change and forestry projects under the Clean Development Mechanism." CDM Dialogue Paper, Center for Clean Air Policy, 2000.

Jagger, T. H., X. Niu, and J. B. Elsner. "A Space-Time Model for Seasonal Hurricane Prediction." *International Journal of Climatology* 22 (2002): 451-465.

Karmali, A. "At what Price" *Carbon Finance,* July, 2005.

King, D. M. "Anatomy of 'Early' Carbon Sequestration Trading: Common Sense Can Prevent Costly and Embarrassing Mistakes." Reprint of: Special Report no. 5, Journal of the Forum for Environmental Law, Science, Engineering, and Finance (FELSEF), Washington, DC, 2002.

King, D. M., and P. J. Kuch. "Will Nutrient Credit Trading Ever Work? An Assessment of Supply and Demand Problems and Institutional Obstacles" *Environmental Law Reporter News and Analysis* (33 ELR 10352), May, 2003.

Knight, F.H. *Risk, uncertainty and profit*. Houghton Mifflin, Boston, 1921.

Knutson, T. R., and R. E. Tuleya. "Increased hurricane intensities with CO_2 -induced global warming as simulated using the GFDL hurricane prediction system." *Climate Dynamics* 15 (7) (1999): 503-519.

Knutson, T. R., R. E. Tuleya, and Y. Kurihara. “Simulated increase of hurricane intensities in a CO_2-warmed climate.” *Science* 279 (5353) (1998): 1018-1020.

Knutson, T. R., R. E. Tuleya, W. Shen, and I. Ginis. “Impact of CO_2-induced warming on hurricane intensities as simulated in a hurricane model with ocean coupling.” *Journal of Climate* 14 (11) (2001): 2458-2468.

Koskela E., and M. Ollikainen. ”Timber Supply, Amenity Values and Biological Risk.” *Journal of Forest Economics* 5 (2) (1999).

Kuhn H., and A. Tucker. Nonlinear programming. *Proceedings of 2nd Berkeley Symposium on Mathematical Statistics and Probabilistics*. University of California Press, 1951, p. 481--492.

Levy, H., and H. M. Markowitz. "Approximating Expected Utility by a Function of Mean and Variance." *American Economic Review* 69 (1979): 308-317.

Lupold, H. M. *Salvage of Storm Damaged Timber, Hurricane Hugo: South Carolina Forest Land Research and Management Related to the Storm*. U.S. Dept. of Agriculture, Forest service, Southern Research Station. Gen. Tech. Rep., SRS-5 pp 21-27, (1996).

Lynne, G. D., and C. E. Kruse. “Potential for Market Systems / Carbon Trading” Report Submitted to University of Nebraska Public Policy Center. Retrieved from http://ppc.unl.edu/publications/documents/carbonsequest_potentialmarket.pdf, August 2005.

MacDicken, K. "A Guide to Monitoring Carbon Storage in Forestry and Agroforestry Projects." Winrock International, 1611 N. Kent St., Suite 600, Arlington, VA 22209, USA, 1997.

Markowitz, Harry M. "Portfolio Selection." *Journal of Finance* 7 (1) (1952): 77-91.

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

McCarl, B.A. "Carbon Sequestration via Tree Planting on Agricultural Lands: An Economic Study of Costs and Policy Design Alternatives." Paper presented at the Energy Modeling Forum, Snowmass, CO, 3-11 August 1998. (http://agecon.tamu.edu/faculty/mccarl/mitigate.html)

McCarl, B. A., B. C. Murray, and U. A. Schneider. "Influences of Permanence on the Comparative Value of Biological Sequestration versus Emissions Offsets." Working Paper 01-WP 282, CARD, Iowa State University, Ames, IA, 2001.

McCarl, B. A., and T. H. Spreen. *Applied Mathematical Programming Using Algebraic Systems*. College Station TX, Texas A&M University, 1997.

McKibbin W., R. Shackleton, and P. Wilcoxen. "The Potential Effects of International Carbon Emissions Permit Trading Under the Kyoto Protocol" Economic Modeling of Climate Change, OECD Workshop Report, OECD Paris. Pp49-80.1998.

McNulty, Steven G. "Hurricane Impacts on US Forest Carbon Sequestration." *Environmental Pollution* 116 (2002): S17-S24.

Meyer, J. "Two-Moment Decision Models and Expected Utility Maximization." *American Economic Review* 77 (1987): 421-30.

Minott Nichola D. "Carbon Sequestration and Its Potential as a Market Mechanism Tool For Sustainable Development" Master of Arts in Law and Diplomacy Thesis, The Fletcher School, Department of International Environmental & Resource Policy, Tufts University, Medford, Massachusetts, May 2004.

Mooney, S., S. Brown, and D. Shoch. "Measurement and Monitoring Costs: Influence of Parcel Contiguity, Carbon Variability, Project Size and Timing of Measurement Events." Winrock International: Report to The Nature Conservancy Conservation Partnership Agreement*,* 2004.

Murray, B.C., B.A. McCarl and H.C. Lee. "Estimating Leakage from Forest Carbon Sequestration Programs." *Land Economics* 80 (1) (2004):109-124.

Murray, B. C., Stephen P. Prisley, Richard A. Birdsey, and R. Neil Sampson. "Carbon sinks in the Kyoto protocol." *Journal of Forestry* September (2000): 6-11.

National Oceanic and Atmospheric Administration, U.S. Department of Commerce, *Hurricane Basics.* May 1999. Retrieved from, http://hurricanes.noaa.gov/pdf/hurricanebook.pdf

Noble, I., M. Apps, R. Houghton, D. Lashof, W. Makundi, D. Murdiyarso, B. Murray, W. Sombroek, and R. Valentini, et al. "Implications of different definitions and generic issues." R. T. Watson, I. R. Noble, B. Bolin, N. H. Ravindranath, D. J. Verado, and D. J. Dokkens (eds.). *Land Use, Land Use Change, and Forestry*. Cambridge U.K.: Cambridge University Press, 2000: 53–156.

Paltsev, S. "Kyoto Protocol: Regional and Sectoral Contributions to Carbon Leakage." *Energy Journal* 22 (4) (2001): 53-79.

Parisi, F. and R. Lund. “Seasonality and Return Periods of Landfalling Atlantic Basin Hurricanes.” *Australian & New Zealand Journal of Statistics* 42 (2000): 271-282.

Pedroni L., and B. Locatelli. “Non-Permanence, Carbon Accounting, and Project Scale.” First Brazilian Symposium on Carbon Sequestration in Agricultural and Forest Systems, Londrina (PR, Brazil), 21-24 October, 2004.

Point Carbon. www.pointcarbon.com

Prestemon, J. P. and T. P. Holmes. “Timber Price Dynamics Following a Natural Catastrophe.” *American Journal of Agricultural Economics* 82 (1) (2000): 145-160.

Reaves, J., S. Conard, R. Birdsey, S. McNulty, and L. Joyce. *USDA Forest Service Global Change Research Program*. Washington, DC, Presented to Climate Change Science Program Office, August 2, (2002).

Reed, W. J. “The Effects of the Risk of Fire on the Optimal Rotation of a Forest.” *Journal of Environmental Economics and Management* 11 (1984): 180-190.

Robison, L. J., and P. J. Barry. *The Competitive Firm's Response to Risk*, New York: Macmillan Publishing Company. 1987.

Rolfe, C. “Additionality: What is it? Does it matter?” Report Prepared for the Technical Committee of the Greenhouse Gas Emission Reduction Trading Pilot Project May 1, 1998 and revised May 8, 1998.

Sampson, Neil R. “Carbon Sequestration: What’s the Best Approach?” Presented at CARBON: Exploring the Benefits to Farmers and Society, Des Moines, Iowa, August 30, 2000.

Sampson, Neil R., and A. R. Sedjo. “Economics of carbon sequestration in forestry: an overview.” *Economics of Carbon sequestration in forestry*. A. R. Sedjo, R. Neil Sampson and Joe Wisniewski eds., pp. S1-S8. New York: CRC Press, 1997.

Schlamadinger, B., and G. Marland. *Land Use & Global Climate Change: Forests, Land Management, and the Kyoto Protocol.* Pew Center on Global Climate Change, June 2000.

Schlamadinger B., L. Aukland, S. Berg, D. Bradley, L. Ciccarese, V. Dameron, A. Faaij, M. Jackson, G. Marland and R. Sikkema. “Forest-Based Carbon Mitigation Projects: Options for Carbon Accounting and for Dealing With Non-Permanence” *UNFCCC Methodological Issues* Sep 4 (2002): 6-21.

Sedjo, R.A. “Forest Carbon Sequestration: Some Issues for Forest Investments.” *Resources for the Future.* Discussion Paper, 01-34, Resources for the Future, Washington, D.C. 2001.

Sedjo, R., G. Marland, and K. Fruit. 2002. “Carbon Emissions Offset Trading: A Tradable Permit System for Temporary Carbon Sequestered.” *CATEP (Concerted Action for Tradable Emissions Permits) Workshop on the Design and Integration of National Tradable Permit Schemes for Environmental Protection*, University College London, United Kingdom, March 25-26 (2002).

Sheffield, R. M., and M. T. Thompson. “*Hurricane Hugo effects on South Carolina's forest resource.”* Asheville, North Carolina: USDA Southeast Forest Experiment Station, Research Paper SE-284, 1992.

Skees, Jerry R. and Barry J. Barnett. "Conceptual and Practical Considerations for Sharing Catastrophic/Systemic Risks." *Review of Agricultural Economics* 21 (1999): 424-441.

Smith, E. "Atlantic and East Coast Hurricanes 1900-98: A Frequency and Intensity Study for the Twenty-First Century." *Bulletin of the American Meteorological Society* 12 2717-2720, December (1999).

Smith, J. "Afforestation and reforestation in the clean development mechanism of the Kyoto Protocol: implications for forests and forest people." *International Journal Global Environmental Issues* 2 (3/4) (2002).

Steinbach, Marc C. "Markowitz Revisited: Mean-Variance Models in Financial Portfolio Analysis." *SIAM Review* 43 (1) (2001):31-85.

Straka, T. M., A. P. Marsinko, J. L. Baumann, and R. G. Haight. "Site Preparation and Tree Planting Costs on Hurricane-Damaged Lands in South Carolina.' *Southern Journal of Applied Forestry* 19(3) (1995): 131-138.

Subak, S. "Replacing Carbon Lost From Forests: An Assessment Of Insurance, Reserves, And Expiring Credits." *Climate Policy* 130 (2003):1-17.

Timber Mart South (http://www.tmart-south.com/tmart/)

UNEP. *Innovative Financing for Sustainability, Finance Initiatives Climate Change* Working Group. Retrieved from http://www.unepfi.org/fileadmin/documents/CEO_briefing_climate_change_2002_en.pdf, September 2005.

UNFCCC. *Methodological Issues Land Use, Land-Use Change and Forestry: Definitions and Modalities for Including Afforestation and Reforestation Activities under Article 12 of the Kyoto Protocol*. Subsidiary Body for Scientific and Technological Advice Eighteenth session Bonn, 4–13 June 2003.

USDA Forest Service. The South's Fourth Forest: Alternatives for the Future, Research Report 24, USDA Forest Service, Washington, D.C., 512 (1988).

Varian, Hal. R. *Microeconomic Analysis* 3rd Edition. W.W. Norton, New York, 1992.

Walker, C. "Managing Risk in a Carbon Constrained World - Insurance as a Facilitator of Emissions Reductions" Fourth Annual Workshop on GHG Emissions Trading – IEA Headquarters Paris, France, October 2004.

Willems S. *Framework for Baseline Guidelines* OECD Information Paper, 2000.

Wong, A., and W. E. Mabee. Forest carbon management in parks and protected areas: An issues analysis. Fifth International SAMPAA Conference, May 11-16, 2003.

Wong, Jenny L. P., and Dutschke, Michael. "Can Permanence be Insured? Consideration of some Technical and Practical Issues of Insuring Carbon Credits from Afforestation and Reforestation." HWWA Discussion Paper No. 235, 2003.

Woodward, Richard T. "Market-Based Solutions to Environmental Problems: Discussion." *Journal of Agricultural and Applied Economics* 32(August 2000):259-266.

Zhao, Y., and W. T. Ziemba. "Mean-Variance versus Expected Utility in Dynamic Investment Analysis." 14th Asian Pacific Finance Conference (Japan). July, 2002.

MANSI GROVER

VITA

EDUCATION

(August'01 – December'05) **Virginia Tech., Blacksburg, VA.**
Ph. D.: Department of Agricultural & Applied Economics
Major: Natural Resources and Environmental Economics, *Minor:* Econometrics

(August'98 - June'00) **Delhi School of Economics, New Delhi, India.**
Master of Arts: Department of Economics, *Major:* Economics

(August'95 - July'98) **University of Delhi, New Delhi, India.**
Bachelor of Arts (Honors): Department of Economics, *Major*: Economics

RESEARCH INTERESTS

- Risk and Uncertainty analysis/ modeling associated with Environmental Markets
- Design and Establishment of Environmental Markets
- Economic and Environmental Sustainability in Agricultural and Forestry Management
- Application of Information Technologies (Including GIS) to Natural Resource Economics
- Incorporating Emissions Trading into Global Trade Analysis Project (GTAP)
- Integration of National Economic Accounts and Environmental Satellite Accounts
- Time Series analysis

SKILL SET

- ***Specialized Applications***: GAMS, ArcGIS, @Risk, Advanced MS-Excel Programming, Lindo, QM, PLMS, MS Access
- ***Statistical Tools***: MATLAB, SAS, SPSS, SHAZAM

PROFESSIONAL EXPERIENCE

Research

(May'04 – August'04) **The Sampson Group, Alexandria, VA.**
Research Intern: Subcontract with National Carbon Offset Coalition as a part of DOE regional grant

Responsibilities Included: Establishing and describing the theoretical economic framework within which a carbon offset trading program is designed; analyzing and describing the practical economic aspects of the program; and describing any further research, development, policies, or incentives that appear to be needed to overcome obstacles or opportunities encountered in the development of the program. The outcome of these research efforts was, "National Carbon Offset Coalition Handbook 2004-2005". I also designed a Cost-Benefit analysis for potential landowners willing to participate in terrestrial carbon trading.

(August'02 - Present) **Virginia Polytechnic Institute & State University, Blacksburg, VA.**
Research Associate*:* Natural Resources Conservation Service, United States Department of Agriculture and EPA funded project; Opportunities and Challenges to Land Based Greenhouse Gas Credit Creation in Virginia.
Responsibilities Include: Synthesis of risk and uncertainty related to terrestrial carbon trading markets, analyzing risk-return trade-offs for forest entrepreneur wishing to sequester and trade carbon, given the risk of carbon loss due to natural disasters, specifically hurricanes and how purchasing private insurance affects the entrepreneur's optimal portfolio of strategies.

(August'01-Dec.'01) **Virginia Tech., Blacksburg, VA.**
Research Associate*:* Chesapeake Bay Program, Scientific & Technical Advisory Committee Workshops on Impediments to Environmentally Sensitive Design.
Responsibilities Included: Literature Synthesis and preparation of research notes on reviewed research material, preparing advisory reports and other related material.

(March'01 – June'01) **National Council of Applied Economic Research, New Delhi.**
Research Associate*:* Sri Ratan Tata Trust funded Rural Infrastructure Project
Responsibilities Included: Literature review, data collection from various agencies and organizing a workshop on initiatives in rural infrastructure sectors in India.

Teaching

(January'03 – May'03) **Virginia Tech., Blacksburg, VA.**
Teaching Assistant*:* Environmental Law, Department of Agricultural and Applied Economics
Responsibilities Include: Grading and designing weekly quizzes, mid-term examinations and final examination.

(January'02 – May'02) **Virginia Tech., Blacksburg, VA.**
Teaching Assistant*:* Environmental Law, Department of Agricultural and Applied Economics
Responsibilities Include: Grading and designing weekly quizzes, mid-term examinations and final examination.

(Nov.'00 – March '01) **University of Delhi, New Delhi, India.**
***Lecturer**: Department of Economics*
Responsibilities Included: Teaching two undergraduate courses, Statistical Methods for Economics and Mathematical Methods for Economics, preparing course notes for students.

Ph.D. THESIS

Incentives for a Forest Landowner to Sequester and Trade Carbon under Uncertainty: Impact of Hurricanes in Southeastern United States (*Proposed Thesis Paper*)

Effect of Private Insurance on Forest Landowners' Incentives to Sequester and Trade Carbon under Uncertainty: Impact of Hurricanes (*Proposed Thesis Paper*) Setting up a Tradable Carbon Offsets System: Risk, Uncertainty and Caveats (*Proposed Thesis Paper*) (For detailed versions of the abstracts for above research documents please visit: http://filebox.vt.edu/users/mgrover/research.htm)

PUBLICATIONS/ PRESENTATIONS

Grover, M., D. Bosch and S. P. Prisley, "Incentives for a Forest Landowner to Sequester and Trade Carbon under Uncertainty: Impact of Hurricanes in Southeastern United States", Paper accepted for publication in the World Resource Review (Forthcoming).

Grover, M. and D. Bosch, "Effects of Private Insurance on Forest Landowners' Incentives to Sequester and Trade Carbon under Uncertainty: Impact of Hurricanes", Paper to be presented at American Agricultural Economics Association Annual Meeting, Providence, Rhode Island, July 24-27th, 2005.

Grover, M., D. Bosch and S. P. Prisley, "Incentives for a Forest Landowner to Sequester and Trade Carbon under Uncertainty: Impact of Hurricanes in Southeastern United States", Paper presented at The 16th Global Warming International Conference & Expo (GWXVI), New York City, April 19-21st, 2005.

Grover, M., "Evaluating Incentives for a Forest Landowner/Entrepreneur to Sequester and Trade Carbon: Impact of Hurricanes in Southeastern United States" Seminar presented at the Department of Agricultural and Applied Economics, Virginia Tech, Blacksburg, VA, USA, December 2004.

Sampson, R. Neil and M. Grover, "*National Carbon Offset Coalition Handbook, 2004-2005*", August 2004 (Available at http://www.ncoc.us/).

Reaves, D. W., K. Stephenson and M. Grover, “Perspectives from accounting.” *Essays on Leadership in Environmental Management.* Erchul, R.A., Bush, H. F., Maisano, Marilyn, R. D., ed., pp. 93-103. Virginia Military Institute, Lexington, Virginia, December 2004.

CLASS PROJECTS

Grover, M. “Assessing the Impact of Uncertain Resolution on Forest Cover and the Definition of a ‘Forest’” Fall 2003.

Grover M. and D. Thomas. “No unit root in GNP: An Implication of Statistical Adequacy” Fall 2003.

MEMBERSHIPS

President, Graduate Students Association, Department of AAEC, Virginia Tech

Association of Environmental and Resource Economists (AERE), US

Southern Agricultural Economics Association (SAEA), US

American Agricultural Economics Association (AAEA), US

Alumni Association, Delhi School of Economics, University of Delhi, N. Delhi, India

Indian Students Association, Virginia Tech

Association for India’s Development (AID) at Virginia Tech