Carbon Offsets as a Cost Containment Instrument: A Case Study of Reducing Emissions from Deforestation and Forest Degradation

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Abstract

Carbon offset is one type of flexibility mechanism in greenhouse gas emission trading schemes that helps nations meet their emission commitments at lower costs. Carbon offsets take advantage of lower abatement cost opportunities from unregulated sectors and regions, which can be used to offset the emissions from regulated nations and sectors. Carbon offsets can also meet multiple objectives; for example, the Clean Development Mechanism in the Kyoto Protocol encourages Annex I countries to promote low carbon sustainable projects in developing countries in exchange for carbon offsets.

Alternatively, the costs under cap-and-trade policies are subjected to uncertainties due to uncertainties about technology, energy markets, and emissions. There are several cost-containment instruments to address cost uncertainties, such as banking, borrowing, safety valve, and allowance reserves. Although carbon offsets are verified to reduce expected compliance costs by providing a surplus of cheap allowances that can be used by Annex I countries to help meet their commitments, they have yet to be studied as a cost-containment instrument. Carbon offsets could potentially be a cost-containment instrument as purchasing carbon offsets during instances of high carbon price volatility could potentially provide some relief from high prices.

This paper analyzes the effect of carbon offsets on carbon prices, specifically under carbon price uncertainty. I use carbon offsets from abatement activities that reduce emissions from deforestation and forest degradation (REDD) as a case study example. My results show that carbon offsets reduce upside costs and thus can be an alternative cost-containment instrument, but cost-effectiveness can be limited by supply uncertainties, offset purchasing restrictions, emission target stringency and competition over demand. Carbon offsets, such as REDD, can serve as a flexibility instrument for developed nations, encourage global participation in reducing GHG emissions, and provide sustainable development support to developing nations.

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1. Introduction

There is scientific consensus that increases in average global temperatures are very likely the result of increases in anthropogenic greenhouse gas emissions, as reported in the 2007 Intergovernmental Panel on Climate Change (IPCC) Synthesis Report (IPCC, 2007). Thirty-seven countries have taken the initiative to regulate greenhouse gas emissions by ratifying the Kyoto Protocol. This agreement amounts to a 5 percent decrease in greenhouse gas emissions from 1990 level emissions during the 2008 through 2012 Kyoto Protocol compliance period.

Although nations commit to targets, there are sectors and other nations that will remain unregulated due to political and administrative unattractiveness. The Kyoto Protocol implements several market-based mechanisms to encourage participation from these unregulated regions and sectors, specifically the Clean Development Mechanism (CDM) and the Joint Implementation (JI). CDM has a two-fold purpose; the mechanism provides incentives for sustainable development in developing countries and provides some flexibility for industrialized (Annex I) countries to meet their emissions targets. Under CDM, Annex I nations finance low carbon sustainable projects in developing areas and in exchange receive Certified Emission Reductions (CER), where one CER is equivalent to the a ton of equivalent carbon dioxide emissions reduced. These CERs can be credited into an Annex I carbon budget thereby making it easier to comply with an emissions reduction commitment. JI is similar to CDM, except that projects occur in regions categorized by the IPCC as '*Economies in Transition*' and Annex I nations acquire Emission Reduction Units (ERU) instead of CERs.

CERs and ERUs from CDM and JI activities are the first application of carbon offsets instruments, where emission reduction activities that occur in unregulated regions and sectors generate emission allowances that can be used to offset Annex I emission targets. Carbon offsets are not limited to these mechanisms; many voluntary carbon offsets markets have been proposed or created such that companies and individuals can purchase reductions to offset their own emissions (MacKerron, et al., 2009).

One major caveat to these offset mechanisms is that to maintain environmental integrity these emission reductions need to be additional to what would have occurred in the absence of the project; otherwise, projects would not actually contribute to actual emission reductions. Under CDM, every project is evaluated by the CDM Executive Board to show additionality and having measurable and verifiable emission reductions. There is some discussion of the establishment of a baseline, whether it truly captures the counterfactual: what happens without CDM and whether projects are attractive without CDM.

Moreover, since the cost of undertaking these projects are cheaper than actual reductions, there is a concern that the carbon offsets will delay reductions or even increase emissions domestically. An assessment of the Kyoto Protocol, by Ellerman et al. (1998), shows that global costs of achieving Kyoto Protocol targets would drop from $120 billion to $54 billion if CERs are allowed and efficiently supplied. In addition, an EPA assessment of the proposed US Leiberman-Warner bill (2008) shows that allowance prices would fall by 71 percent with unlimited domestic and international offsets. As a result, carbon offsets have been criticized as potentially weakening the market price signal for carbon-intensive commodities, thereby reducing the incentive to change consumption patterns for consumers in developed countries and reducing the incentive for industries to invest in low carbon technologies. In addition, since not all carbon offsets are the same, there is a concern that some offsets may produce carbon leakage by pushing carbon intensive operations in unregulated regions thereby weakening the integrity of emission reductions.

The costs under emissions cap-and-trade policies are subjected to uncertainties due to uncertainties about technology, energy markets, and emissions, to name a few. Carbon price volatility can be particularly troublesome just as any other market. There are a number of cost containment mechanisms that address carbon price volatility, most commonly: banking and borrowing, safety valve, and allowance reserves. However, carbon offsets have yet to be studied as a potential cost-containment instrument. Carbon offsets are verified to reduce expected compliance costs by providing a surplus of cheap allowances that can be used by Annex I countries to help meet their commitments, thereby reducing expected costs of an emission reduction policy, as shown by the EPA assessment of the proposed US Leiberman-Warner bill (2008) and Ellerman et al. (1998). Therefore, using carbon offsets during instances of high carbon price volatility could potentially provide some relief from high prices; therefore, carbon offsets could potentially be a cost-containment instrument. **Therefore, this paper will investigate whether carbon offsets can reduce carbon price volatility, specifically upside cost uncertainty; I will use deforestation reduction projects as a case study example, which are known as Reduced Emissions from Deforestation and forest Degradation (REDD).**

Deforestation is reported to account for approximately 20 percent of global greenhouse gas emissions, second to energy production and higher than those from the transportation sector.
REDD aims to reduce emissions by reducing deforestation through an economic value placed on the carbon stored in forests; this provides incentives for developing countries to reduce emissions from forested lands and invest in low-carbon paths to sustainable development. This mechanism provides an opportunity to reduce GHG emissions and incentivizing sustainable development in these developing countries. Unfortunately, REDD activities are not currently considered valid CDM projects, due to disagreements over assignment of credits from carbon sinks in Kyoto and subsequent negotiations in The Hague (van't Veld and Plantinga, 2004). However, the REDD mechanism is considered to play an active role in the post-Kyoto framework based on the Copenhagen Accord (UNFCC COP 15, 2009).

Using REDD as a case study example, this paper will show that carbon offsets exhibit cost containment properties, specifically reducing upside carbon price uncertainties. Therefore, carbon offsets, such as REDD, can serve as a flexibility instrument for developed nations, encourage global participation in reducing GHG emissions, and provide sustainable development support to developing nations. However, cost containment effectiveness is reduced with increased competition over demand for offsets and offset demand restrictions. In addition, REDD supply uncertainties further reduce cost containment effectiveness.

REDD is analyzed through four different trading scenarios to illustrate the effect of competition on cost-containment effectiveness. In addition, I analyze the effect of offset demand restrictions on cost-containment effectiveness. The proposed American Clean Energy and Security Act of 2009 (H.R. 2454, Waxman-Markey Bill) has provisions that limit the amount of offsets that can be purchased by the US, specifically a limitation of 2 billion metric tons (bmt) of CO_2 offsets are allowed per year, where 1 bmt CO_2 offsets are from domestic sources and the rest are from international sources. Therefore, I examine the restricted demand case for the US, where it can only acquire 1 billion metric tons of REDD as laid out in the proposed Waxman-Markey Bill to examine the effect of demand restrictions.

These trading and offset demand restriction scenarios will be explored both deterministically and stochastically. Deterministic analysis will show the effects of REDD on expected costs without cost uncertainty. Stochastic analysis will show the effects of REDD under cost uncertainty and determine whether REDD reduces upside carbon prices. In addition, two sets of REDD supply scenarios are tested stochastically; these supply scenarios represent high to low opportunity costs based on fast to slow deployment rates and high to low opportunity costs based on a fast deployment rate scenario.

Chapter 2 provides background information on carbon offsets, REDD, and cost-containment mechanisms. Chapter 3 provides a motivational example for the research question: whether carbon offsets, such as REDD, do exhibit cost containment properties. Chapter 4 explains modeling, methodology, and respective assumptions. Results and discussion is provided in Chapters 5 and 6.

2. Background

2.1 Carbon Offsets

In a GHG emission reducing policy, several flexibility mechanisms exist to help nations meet emission reduction commitments at lower costs. The two main mechanisms are emissions trading and carbon offsets. Emissions trading allow firms and nations to take advantage of cheaper abatement options within regulated sectors and regions; linked trading schemes can further expand the pool of available abatement options within linked regions. Carbon offsets allows firms and nations to take advantage of abatement opportunities from unregulated sectors and regions to offset their own emissions. Both mechanisms take advantage of the availability of cheaper abatement options in other regions and sectors thereby reducing the costs of complying with emission reduction targets.

An early application of pollution offsets was in the Clean Air Act. The purpose of the Clean Air Act was to protect and improve the air quality in the United States through research and supporting state and local government efforts (EPA, 1963). Originally, the Clean Air Act (1963) had not allowed new emission sources in non-attainment areas, which were regions that had not met a specified ambient standard by the 1975 deadline. Subsequently, due to concerns that this restriction would slow economic growth in these non-attainment areas, in 1976, the Environmental Protection Agency (EPA) amended the act to include an '*offset-mechanism*' provision; this allowed new emission sources to enter a non-attainment area, if they can offset their emissions from existing polluters. This provision essentially created the framework for carbon offsets (Stavins, 2004).

The Kyoto Protocol incorporates multiple flexibility mechanisms, including emissions trading, the Clean Development Mechanism (CDM) and Joint Implementation (JI), which operate similar to the offset-mechanism in the Clean Air Act by taking advantage of lower marginal abatement costs in different regions and sectors. GHG reductions occurring in Annex I nations generate Emission Reduction Units (ERU) which can be traded between Annex I nations per Article 6 of the Kyoto Protocol (UNFCCC, 1998). CDM and JI have additional objectives that aim to foster global participation, sustainable development, and increase mitigation opportunities. Since CDM projects occur in non-Annex I nations, the emission reductions from CDM projects undergo a certification process to ensure reductions are measurable, verifiable, and additional. This certification process generates Certified Emission Reductions (CERs), which can be used by Annex I nations to comply with their respective GHG emission targets. The emission reductions from CDM and JI that are traded with Annex I nations are carbon offsets.

The use of carbon offsets reduces expected costs since Annex I nations can use CERs to help meet their emission reduction targets thereby reducing domestic GHG emission abatement efforts; since these allowances originate from unregulated sectors and regions, estimates of reductions in expected compliance costs are significant. The EPA analyzed the effect of offsets on the Climate Security Act of 2008 (S.2191, Lieberman-Warner Bill); it showed that expected compliance costs would fall 71 percent through the use of unlimited domestic and international offsets. In addition, EPA performed sensitivity analysis on offset limitations and showed that if international offsets are restricted to 15 percent of the compliance obligation, carbon prices reduce by 26 percent. If international offsets are banned and domestic offsets are limited to 15 percent of the compliance obligation, carbon prices increase by 34 percent and increase by 93 percent when both international and domestic offsets are banned.

Moreover, these large reductions in expected compliance costs can weaken price signals for consumers and firms to change behavior; high prices incentivize consumers to reduce energy consumption and firms to invest in new technologies. Tavoni et al. (2006) shows through an intertemporal optimization model that the introduction of forestry offsets reduce improvements by the energy sector and policy-induced change in clean technologies by two to three decades. Therefore, carbon offsets are criticized for delaying important early investments in clean technologies by relying on foreign emission reductions.

2.2 Reducing Emissions from Deforestation and forest Degradation

According to the Article 2 of the Kyoto Protocol, GHG emission reductions can be met through the management of carbon sources and sinks, where acceptable carbon sinks are defined under specific human-induced activities in the land use, land-use change and forestry (LULUCF) sector (UNFCCC, 1998). Under LULUCF, there are three accepted mitigation options: afforestation, reforestation, and deforestation avoidance (Watson et al., 2000; Asner et al., 2005). Afforestation involves the conversion of long-term non-forested land to forest; reforestation activities convert recent non-forest land to forest, and deforestation avoidance projects prevent the conversion of carbon-rich forests to non-forest land. These three mitigation efforts are expected to reduce total global greenhouse gas emissions by up to 25 percent (Niles et al., 2002; Barker et al., 2007).

The Kyoto Protocol allows afforestation, reforestation and deforestation avoidance projects since 1990 as options that can be used to help Annex I nations meet their commitments. However, the Protocol left out rules and guidelines defining eligible projects, reporting and verifiability methods, which were defined in subsequent Conference of Parties (COP) agreements following the Kyoto Protocol. In COP 6 held at Bonn, negotiators agreed on the basic principles to govern LULUCF activities and the definitions for afforestation, reforestation and deforestation. The agreements add the following eligible activities under Article 3.4: forest management, cropland management, grazing land management, and vegetation, subject to certain conditions (UNFCCC, 2002). Furthermore, CDM LULUCF activities are limited to afforestation and reforestation only (UNFCCC COP 7, 2001).

According to the United Nations Food and Agriculture Organization (FAO), deforestation is defined as forest changes that contribute to loss of tree cover of at least 10 percent; forest degradation is the reduction of forest biomass from non-sustainable harvest or land-use practices (O'Brien, 2000; Asner, 2005). FAO reports that forests account for about half of the global terrestrial carbon pool, and deforestation in tropical regions account for about 20 percent of the global greenhouse emissions (Houghton, 2005). Moreover, tropical forests store about 50 percent more carbon than non-tropical forests; these tropical areas fall outside the Annex I region, mainly Indonesia and Brazil, which under current deforestation rates accounts for about 80 percent of annual Annex I emissions reduction targets (Corbera et al., 2009). Therefore avoided deforestation projects in these carbon-rich tropical areas would not be eligible to generate ERUs or CERs. Reductions in deforestation and forest degradation in these developing regions are collectively referred as REDD.

Estimates of mitigation potential from REDD range from 2.6 GtCO2e to 3.3 GtCO2e per year by 2030 (Eliasch, 2008; Vattenfall, 2007; Stern, 2006). The uncertainties in mitigation potential from REDD poses an underlying problem for negotiators by complicating the determination of additionality and verifiability. These high-deforestation countries also have underlying infrastructure issues, as they lack leadership, secure property rights, resources and equipment, and government corruption exacerbates the effectiveness of support activities (Corbera et al., 2009). In addition, deforestation reduction projects are in danger of non-permanence as forests can be both a carbon sink and source, depending on age, management, environmental conditions and disturbances that alter their composition (Watson et al., 2000; Rosenbaum et al., 2004; Dale et al., 2001). In addition, there are large uncertainties in GHG mitigation due to the variety of carbon sequestration potentials among different trees. These uncertainties create liabilities for verifiability of emission reductions and determining baselines for business-as-usual to ensure additionality. However, it has been argued that REDD can be more cost-effective than other mitigation options because it does not require the development of new technology, except for monitoring (Stern, 2006), and it can generate co-benefits such as employment, environmental conservation and poverty alleviation (Corbera et al., 2009).

Some foreign assistance currently exists to address deforestation; however based on current rates, it is failing to significantly abate global deforestation. Recent studies estimate that to achieve a substantial reduction of emissions from deforestation, funds of at least $5 billion per year are needed. In contrast, the current level of funding from foreign assistance, as of March 2009, totaled less than $1 billion (Corbera et al., 2009), is not enough to significantly curb deforestation-related emissions. In addition, a FAO Assessment reports that deforestation grew significantly between 1990 and 2005 with few signs of slowing down (Corbera et al., 2009). Moreover, existing deforestation policies (conservation policies and sustainable forest management) have not been effective due to insufficient staffing, poorly defined multi-stakeholder and institutional arrangements, lack of management leadership and undermining political environments (Stoll-Kleeman et al., 2006). Therefore, current efforts to reduce deforestation have been unsuccessful; incorporating REDD into CDM can potentially provide these needed reductions. Current CDM transactions reported to generate about $50 billion to $120 billion per year, incorporating deforestation in a carbon market can provide sufficient funding to significantly reduce emissions from deforestation (Corbera et al., 2009).

Moreover, funding cannot entirely solve the deforestation problem, as policy needs to address deforestation drivers directly in order for deforestation funding to be cost-effective. A 152-subnational case study showed that for tropical deforestation, economic and policy/institutional factors play a major role in driving deforestation (Geist and Lambin, 2001). Drivers of deforestation vary from country to country (Tole, 1998) and effective policies and mechanisms should ensure that deforestation drivers are addressed and highly-deforested countries receive sufficient funding. In response to current deforestation-reducing activities and the need for further support of REDD efforts in developing countries, the Bali Action Plan encourages Annex I countries to support voluntary efforts to reduce emissions from deforestation and forest degradation through: capacity-building assistance, provide technical and technology transfer assistance, efforts to address deforestation drivers, and advance research on addressing methodological issues to ensure verifiability and additionality (UNFCCC COP 13, 2008). In anticipation of incorporating REDD as a post-Kyoto mechanism, the UN-REDD Programme, in collaboration with UN Food and Agricultural Organization, UN Development Programme, and UN Environment Programme, was created to help REDD host countries prepare to participate in a REDD mechanism through national policies and involvement of all stakeholders.

Currently, forestry offsets are not standard in all emission permit markets. Due to uncertainties in forestry projects and regional preferences to encourage clean technology investment, forestry credits are not accepted in the European Union Emissions Trading Scheme (EU ETS), which is the largest emissions trading system in operation. According to the draft amendment of the EU ETS Directive published by the EU Commission, forestry credits will continue to be excluded from the EU ETS after 2012 (Streck et al., 2009). On the other hand, forestry credits are accepted in other smaller trading systems, such as the New South Wales Greenhouse Gas Abatement Scheme, the Regional Greenhouse Gas Initiative (RGGI), and the Chicago Climate Exchange (Streck et al., 2009). Due to limited market entry, forestry offsets have yet to provide real emission reduction benefits; therefore acceptance of REDD in CDM, with sound policies and supporting infrastructure, can potentially further expand the availability of more GHG mitigation options and reduce deforestation and forest degradation.

The UNFCCC created the framework to encourage activities that address the shortfalls of REDD implementation in Kyoto Protocol from the supply side to make REDD available for meeting commitments. On the demand side, studies have shown that carbon offsets further help reduce expected compliance costs. This paper aims to show that carbon offsets, such as REDD, can also address cost uncertainties for Annex I nations.

2.3 Cost Containment

In greenhouse gas emission reduction policies, the two policy instruments commonly discussed are a carbon tax (price) and cap-and-trade (quantity). In a deterministic scenario, where the costs and benefits of emission abatement are completely known, both instruments yield the same outcome, i.e., the same emission reductions at the same cost. Under uncertainty in abatement costs, a tax policy will have uncertainty in emissions. Conversely, a cap-and-trade policy will have uncertain carbon prices as there is no flexibility in emission targets.

Uncertainty in costs and emissions play a vital role in the economy and environmental integrity. Uncertainty in carbon prices is troublesome as energy plays a vital role in any economy. Allowance prices could affect energy prices, the rate of inflation, and the value of goods and services, making investment decisions difficult (CBO, 2008). The causes of volatility can be attributed to the introduction of new technologies, energy efficiency gains, introduction of alternative sources of energy, and uncertainty about emissions; these sources can vary the cost of complying with a policy. Uncertainty in emissions is also a cause for concern as it can undermine emission target commitments and result in undesirable environmental complications from increasing emissions. Since greenhouse gases are a stock pollutant, GHG concentrations are based on accumulation of emissions over long periods of time; therefore, periods of high emissions can undermine long term GHG concentration objectives. Therefore, the policy instrument of choice can pose both environmental and economic implications.

Many studies validate the preference of a tax over a cap-and-trade policy for climate change. Most notably, Weitzman (1974), through a model, found that the relative shape of the marginal benefit and costs curves for pollution abatement determines the preference of one instrument over the other. He concluded that a price instrument is favored over quantity when marginal costs are steeper than marginal benefits. Pizer (2002), through Monte Carlo Simulations, demonstrates that climate change benefits are fairly linear thus justifying the preference for price policy in climate change policy. The basic reasoning is that because marginal benefits are flatter than marginal costs, changes in emissions would have a larger effect on costs than benefits; therefore, a price policy would be more advantageous. Moreover, the US Congressional Budget Office (CBO) study, on *Policy Options for Reducing CO2 Emissions* (2008), finds that a tax policy absorbs price fluctuations and encourages firms to reduce further when marginal costs are low. Furthermore, when considering the effects of dynamics on cost and emissions, specifically correlation of cost shocks with time, discounting, stock decay, and rate of benefits growth with respect to welfare, Newell and Pizer (2003) show that a price can produce five times the welfare benefits of a quantity instrument when accounting for dynamic effects.

Unfortunately, the US adoption of a carbon tax policy is politically unappealing due to the political aversion to tax policies. The US has a successful history with cap-and-trade policy in the Acid Rain Program, which created a system tradable of SO_2 allowances. This bias towards cap-and-trade is evident in recent proposals and the Regional Greenhouse Gas Initiative (RGGI) in the Northeast; therefore, there is a strong preference for cap-and-trade policies for greenhouse emissions.

This preference for cap-and-trade policies makes the emission trading scheme vulnerable to price uncertainties. There are several cost containment instruments that can be implemented into a cap-and-trade policy to address price volatility, such as banking, borrowing, safety valve, and allowance reserves. These instruments address different types of cost uncertainties, mainly short term and/or start up uncertainties; therefore, multiple instruments can be incorporated in any one policy (Webster et al., 2008a).

Banking and borrowing add inter-temporal flexibility by allowing firms to bank current period allowances for future use or borrowing future allowances to use in the present. This can help reduce short term price volatility. A study by Fell et al. (2008) showed that the use of banking can reduce the welfare differences between a fixed cap-and-trade and carbon tax by 25 percent. Additionally, the effectiveness of a bank can be improved with the availability of a large bank or borrowing for the initial compliance year, as carbon prices are expected to have high volatilities during the policy's inception due uncertainties about abatement and low volume of allowances (Fell et al., 2008). These instruments allow firms to have more control over the management of their emissions over time.

In addition, a hybrid (cap-and-trade and tax) instrument can potentially offer the benefits of both policies, while compensating for their shortfalls thus reducing total cost (Roberts and Spence, 1976). This type of instrument needs to have considerable uncertainty in benefits as well as costs to be effective. A safety valve mechanism, which is considered to be a hybrid instrument, places a price ceiling on carbon prices, which controls for upside carbon price volatility. When carbon prices exceed the trigger or ceiling price, an unlimited amount of allowances are released into the market and available until prices drop below the trigger or ceiling price. This mechanism is effective for short term of start-up uncertainties; it poses concerns for long term uncertainties, where availability of unlimited allowances can cause emission targets to be exceeded during periods of sustained high carbon prices. The effectiveness of a safety valve is dictated by the trigger price: a low trigger price essentially converts a cap-and-trade policy into a tax policy as the safety valve will likely be triggered more often than not; a high trigger price reduces the likelihood of triggering, and at the limit the policy is essentially a pure cap-and-trade. While the safety valve provides a relief from upside costs, a policy can also address downside costs risks by implementing a price floor, which would operate similarly to a safety valve.

An allowance reserve is similar to a safety valve, but there are a limited amount of allowances entering the market when the trigger price is exceeded. This is mainly to address concerns that unlimited allowances will produce excessive amounts of additional emissions, especially when safety valve and banking are used concurrently. These two mechanisms can undermine environmental goals if firms can bank an unlimited amount of allowances when the safety valve is triggered, which would undermine reduction goals in future years. The allowance reserve mechanism would improve the effectiveness of a cap-and-trade policy under price uncertainty and make it politically attractive for environmentalists (Murray et al., 2008).

In addition, linking policies between countries allows linked nations to achieve emission reductions cost-effectively. A major limitation of these instruments is that it can make linking trading schemes with other countries unattractive, especially for countries that do not allow these types of cost containment mechanisms. Linking makes these instruments available for every linked trading scheme regardless if it is or is not allowed in scheme. Furthermore, reductions in carbon prices can lead to concerns of reduced investment incentives due to expectations of lower carbon prices.

3. Motivational Example

In this section, I present a motivational example to illustrate the potential of carbon offsets as a cost containment mechanism.

The costs of abating stock pollutants, such as greenhouse gas emissions, can be represented by the marginal abatement cost (MAC) curve. It illustrates that abatement costs increase with increasing reductions since low cost abatement options are exhausted first. Figure 1 illustrates a representative MAC curve from Morris et al. (2008), which represents the US marginal abatement costs in 2050. We use this MAC curve for the motivation example.

Carbon offsets can reduce compliance costs by reducing domestic reduction efforts. Since marginal costs rise quickly with increasing abatement, for a given offset amount, offsets can generate larger carbon price reductions for larger emission reduction targets than for smaller targets. If I consider a 'US 50% policy' in 2050, this requires an abatement of 9132 million metric tons (mmt) of CO_2, which yields a carbon price of \$109 per ton CO_2 from Figure 1. If I assume US acquires 500 mmt CO_2 of carbon offsets, which is relatively small relative to the target (5% of the target), the new target would be 8632 million metric tons; this yields a carbon price of \$98 per ton CO_2, which is an 11 percent reduction from the original target without any offsets.

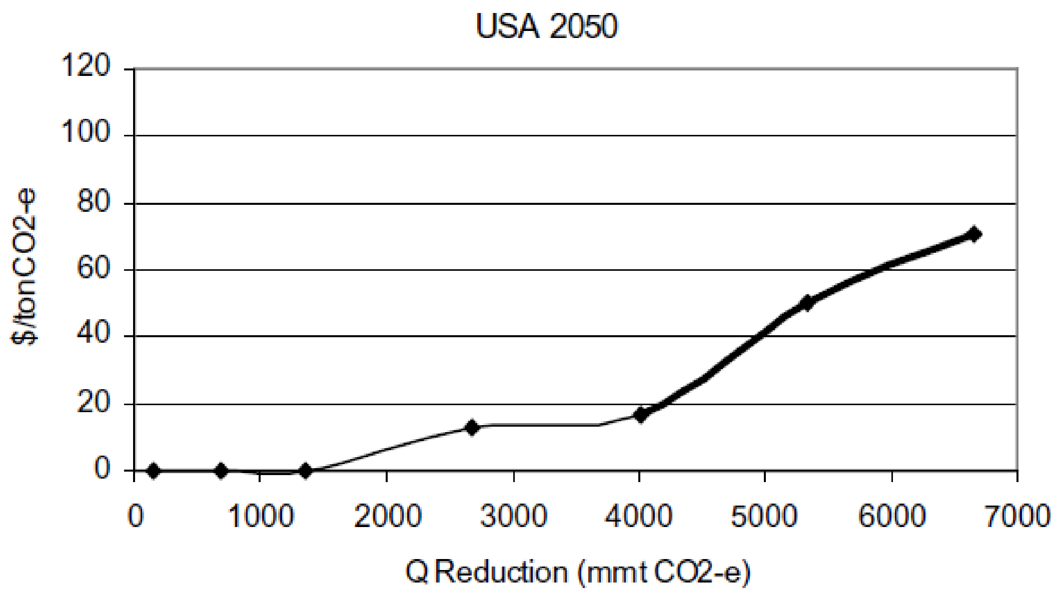

Figure 1. US 2050 MAC Curve (Morris et al., 2008)

As mentioned in Chapter 2, abatement costs are likely to be subjected to uncertainties for various reasons, such as uncertainties in abatement technologies, emission targets, and weather. These uncertainties will result in carbon price volatility. I will illustrate these effects in the MAC curve shown in Figure 1.

First, I fit a polynomial curve to the MAC curve, in the form of $y = Ax^3 + Bx^2 + Cx + D$, to obtain an algebraic expression for the MAC curve. For MAC curve in Figure 1, the polynomial fit is: $-4E\text{-}11x^3 + 2E\text{-}6x^2 - 0.0031x + 0.9704$. This polynomial fit shows that higher order effects beyond the second-order term may play a diminished role, as shown by the smaller coefficient value.

I illustrate uncertainties in carbon prices by imposing a distribution on each polynomial coefficient (A, B, C, and D). For this example, I replace only one coefficient at a time with a distribution ranging from half to twice the nominal coefficient value. The same process is completed for the other coefficients, and I get a distribution of carbon prices as shown in Figure 2 for each coefficient uncertainty.

Figure 2 illustrates the effect of uncertainty on carbon prices. These figures overlay the nominal MAC curve with MAC at the upper and lower bounds of the imposed coefficient distribution. With an emissions reduction target of 9132mmt CO_2 from above, uncertainties in coefficients A, B, and C produce high carbon price volatilities. In addition, the effect of the 500mmt CO_2 carbon offset on carbon price varies over the coefficient distribution; this is mostly evident in 'Uncertainty in B' results, the reduction in carbon price is greater in the upper bound than the lower bound, as shown by the circles in each curve (dark-colored circle represents original target, light-colored circle represents new target with offsets).

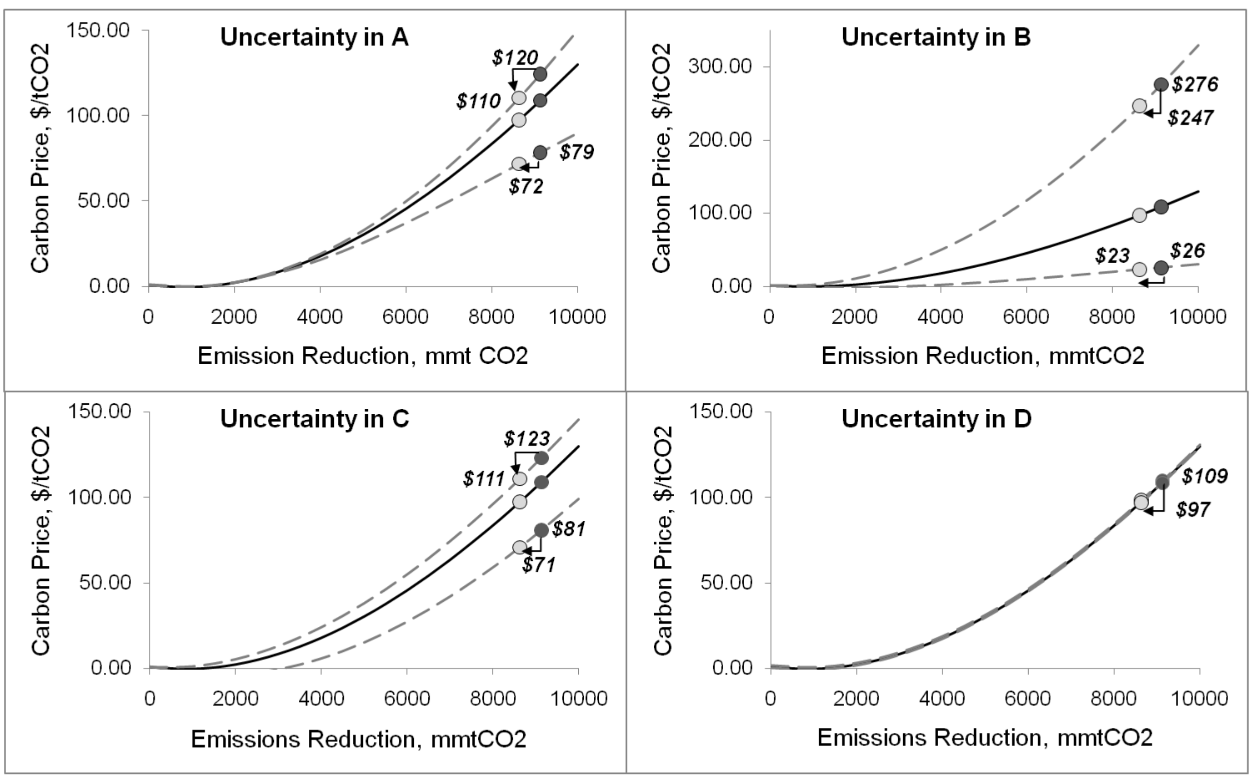

Figure 2. MAC curves with uncertainty bounds

I further examine the role of carbon offsets under MAC uncertainties using Monte Carlo Analysis. Using the imposed probability distributions on each polynomial coefficient, I extract 10,000 random samples from each coefficient distribution; these samples are used simulate uncertainties in marginal abatement costs. For coefficient A, instead of the half to twice distribution, I imposed a normal distribution, with a standard deviation of 4E-11 since values under –1.81E-10 yield negative prices. Using these samples, I compare the distribution of carbon prices at the original target (9132 mmt CO_2) and new target with the 500mmt CO_2 carbon offset (8632mmt CO_2).

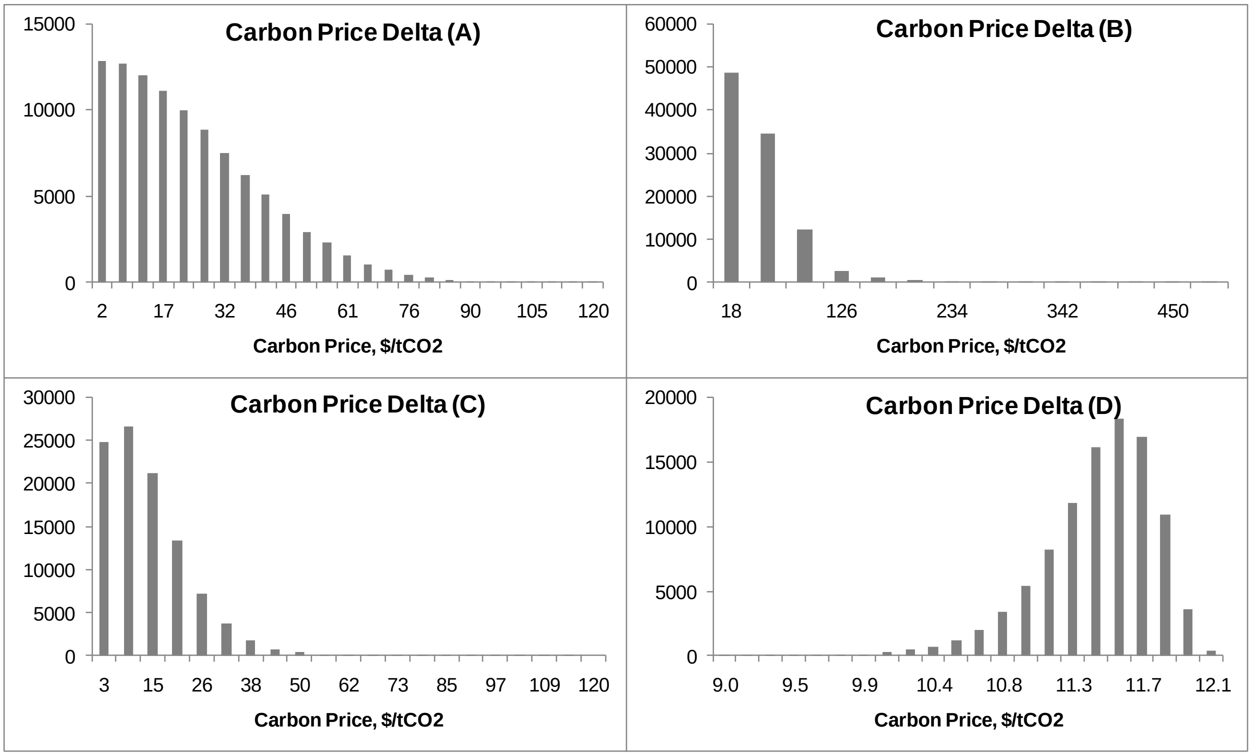

Figure 3. Delta Carbon Price between Nominal and Respective Coefficient Uncertainty

The carbon price reduction due to carbon offsets is illustrated in Figure 3, which shows the distribution of carbon price reductions. The greatest reduction potential comes from the higher order terms, represented by coefficients A and B. The price reductions are greater for higher order terms meaning that the upper tail end of the carbon price distribution is reduced, reducing upside cost uncertainties. For this MAC, the offset has a larger effect on carbon price for the second-order term than the third order term; this result is unique to the MAC curve used as the third-order coefficient (-4E-11) is 4 orders of magnitude smaller than the second-order coefficient (2E-6).

Therefore, small reductions in emission reduction targets from carbon offsets can potentially result in large reductions in carbon price. This is especially true for higher order uncertainties in the MAC curve. Therefore, this presents an opportunity for offsets, such as REDD, to reduce upside cost uncertainties.

4. Methodology

In this chapter, I describe the framework and assumptions used to simulate the effect of REDD offsets. The analysis requires an assumption about the linked emissions trading schemes into which offsets would be traded, along with respective regional GHG emission commitments. In addition, the following REDD details are needed: quantity of REDD available (REDD supply), and REDD supplying regions with their respective business-as-usual baselines to ensure additionality.

Moreover, as verified in the EPA study of the Lieberman-Warner bill (EPA, 2008) through restrictions on domestic and/or international offsets, offset scarcity impacts expected compliance costs; therefore, offset scarcity could also impact cost-containment. Scarcity is influenced by changes in the supply of and the demand for offsets. For REDD, supply is the amount of REDD credits allocated to these high-risk deforestation regions, and demand is the amount of REDD credits acquired by each region. Therefore, I analyze several limitations on the demand for and supply of REDD to determine the scarcity effects on cost-containment.

I examine two factors that influence demand: competition (number of buyers) and offset demand restrictions. Competition increases overall demand for offsets thereby making offsets scarcer for all offset buyers, as the supply of offsets cannot compensate for the increase in demand. Offset demand restrictions are limitations on the amount of offsets allowed to enter an emissions trading scheme. I simulate competition by modeling four trading scenarios, with increasing number of REDD buyers, to represent low to high competition. In addition, I apply the 1 billion metric ton CO_2 international offset restriction from the Waxman-Markey Bill (H.R. 2454) to simulate US offset demand restrictions.

There are uncertainties that impact the allocation of offsets in each region, which can be influenced by a number of factors, such as certification and opportunity costs. I examine supply uncertainties based on opportunity costs and deployment uncertainties. I generate two alternative supply probability distributions representing the following two supply scenarios: (1) combined opportunity and deployment uncertainties, and (2) opportunity cost uncertainties based on fast deployment. I examine these two supply scenarios via Monte Carlo simulation; using randomly drawn samples from these two distributions, I analyze the two different supply scenarios with REDD to determine the effect of supply uncertainties on cost-containment.

I model REDD both deterministically and stochastically. The deterministic results illustrate the effects of REDD on expected compliance costs under the different trading scenarios and under US offset demand restrictions. The stochastic analysis assesses REDD offsets on carbon price and supply uncertainties under the different trading scenarios and US offset demand restrictions. To model cost uncertainties, I use Monte Carlo simulation with 400 samples that are drawn from probability distributions for 110 EPPA model parameters that are found to impact emissions and cost. I simulate the effects of including REDD, under these cost uncertainties, for each of the different trading scenarios and US offset demand restrictions to determine whether REDD offsets exhibit cost-containment behavior and whether competition and offset demand restrictions limit cost-containment effectiveness. The supply uncertainties are assessed similarly to cost uncertainties; I incorporate the samples drawn from the two supply distributions with the cost uncertainty samples and assess the different trading scenarios and US offset demand restrictions.

I examine four trading scenarios with increasing competition, with the following designated REDD buyers: (1) US only; (2) Canada, Japan, European Union, Australia, New Zealand added; (3) China added; (4) All regions. I will refer trading scenario 2 as 'Annex 1' even though it does not include all Annex 1 countries.

I model the offset restrictions in the proposed American Clean Energy and Security Act of 2009 (H.R. 2454, Waxman-Markey Bill) as the offset demand restriction scenario. The bill has a provision that limits domestic and international offsets to two billion metric tons (bmt) of CO_2 – one bmt for domestic and the rest for international offsets; this can limit cost containment effectiveness as it artificially makes offsets scarce within the US.

All scenarios described above are analyzed using a computational general equilibrium (CGE) model, MIT Emissions Prediction and Policy Analysis (EPPA) Model. The following sections will discuss the supply and demand assumptions and emission targets in further detail as well as how they are incorporated in the EPPA model.

4.1 Emissions Prediction and Policy Analysis (EPPA) Model

I use Version 4 of the Emissions Prediction and Policy Analysis (EPPA) model. The EPPA model is a CGE model developed by the MIT Joint Program on the Science and Policy of Global Change. The EPPA model is a multi-region, multi-sector recursive-dynamic representation of the global economy (Paltsev et al., 2005). In a recursive-dynamic solution economic actors are modeled as having "myopic" expectations.[1] This assumption means that current period investment, savings, and consumption decisions are made on the basis of current period prices.

The EPPA model is built on the GTAP dataset (Hertel, 1997; Dimaranan and McDougall, 2002), which accommodates a consistent representation of energy markets in physical units as well as detailed data on regional production, consumption, and bilateral trade flows. Besides the GTAP dataset, EPPA uses additional data for greenhouse gases and air pollutant emissions based on United States Environmental Protection Agency inventory data.

The model is calibrated based upon data organized into social accounting matrices (SAM) that include quantities demanded and trade flows in a base year denominated in both physical and value terms. A SAM quantifies the inputs and outputs of each sector, which allow for the calculation of input shares, or the fraction of total sector expenditures represented by each input. Much of the sector detail in the EPPA model is focused on providing a more accurate representation of energy production and use as it may change over time or under policies that would limit greenhouse gas emissions. The base year of the EPPA model is 1997. From 2000 the model solves recursively at five-year intervals. Sectors are modeled using nested constant elasticity of substitution (CES) production functions (with Cobb-Douglass or Leontief forms). The model is solved in the Mathematical Programming System for General Equilibrium

[1] The EPPA model can also be solved as a forward looking model (Gurgel *et al.*, 2007). Solved in that manner the behavior is very similar in terms of abatement and CO_2-e prices compared to a recursive solution with the same model features. However, the solution requires elimination of some of the technological alternatives.

(MPSGE) language as a mixed complementarity problem (Mathiesen, 1985; Rutherford, 1995). The resulting equilibrium in each period must satisfy three inequalities: the zero profit, market clearance, and income balance conditions (for more information, see Paltsev et al., 2005).

The level of aggregation of the model is presented in Table 1. The model includes representation of abatement of CO_2 and non-CO_2 greenhouse gas emissions (CH_4, N_2O, HFCs, PFCs and SF_6) and the calculations consider both the emissions mitigation that occurs as a byproduct of actions directed at CO_2 and reductions resulting from gas-specific control measures. Targeted control measures include reductions in the emissions of: CO_2 from the combustion of fossil fuels; the industrial gases that replace CFCs controlled by the Montreal Protocol and produced at aluminum smelters; CH_4 from fossil energy production and use, agriculture, and waste, and N_2O from fossil fuel combustion, chemical production and improved fertilizer use. More detail on how abatement costs are represented for these substances is provided in Hyman et al. (2003).

Non-energy activities are aggregated into six sectors, as shown in the table. The energy sector, which emits several of the non-CO_2 gases as well as CO_2, is modeled in more detail. The synthetic coal gas industry produces a perfect substitute for natural gas. The oil shale industry produces a perfect substitute for refined oil. All electricity generation technologies produce perfectly substitutable electricity except for Solar and Wind technology, which is modeled as producing an imperfect substitute, to reflect intermittent output.

The regional and sectoral disaggregation is also shown in Table 1. There are 16 geographical regions represented explicitly in the model including major countries (the US, Japan, Canada, China, India, and Indonesia) and 10 regions that are an aggregations of countries. Each region includes detail on economic sectors (agriculture, services, industrial and household transportation, energy intensive industry) and a more elaborated representation of energy sector technologies.

Table 1. EPPA Model Details.

Country or Region [†]	***Sectors***	**Factors**
Developed	***Final Demand Sectors***	Capital
United States (USA)	Agriculture	Labor
Canada (CAN)	Services	Crude Oil Resources
Japan (JPN)	Energy-Intensive Products	Natural Gas Resources
European Union+ (EUR)	Other Industries Products	Coal Resources
Australia & New Zealand (ANZ)	Transportation	Shale Oil Resources
Former Soviet Union (FSU)	Household Transportation	Nuclear Resources
Eastern Europe (EET)	Other Household Demand	Hydro Resources
Developing	***Energy Supply & Conversion***	Wind/Solar Resources
India (IND)	Electric Generation	Land
China (CHN)	Conventional Fossil	
Indonesia (IDZ)	Hydro	
Higher Income East Asia (ASI)	Nuclear	
Mexico (MEX)	Wind, Solar	
Central & South America (LAM)	Biomass	
Middle East (MES)	Advanced Gas (NGCC)	
Africa (AFR)	Advanced Gas with CCS	
Rest of World (ROW)	Advanced Coal with CCS	
	Fuels	
	Coal	
	Crude Oil, Shale Oil, Refined Oil	
	Natural Gas, Gas from Coal	
	Liquids from Biomass	
	Synthetic Gas	

[†] Specific detail on regional groupings is provided in Paltsev *et al.* (2005).

When emissions constraints on certain countries, gases, or sectors are imposed in a CGE model such as EPPA, the model calculates a shadow value of the constraint which can be interpreted as a price that would be obtained under an allowance market that developed under a cap and trade system. Those prices are the marginal costs used in the construction of marginal abatement cost (MAC) curves. They are plotted against a corresponding amount of abatement, which is the difference in emissions levels between a no policy reference case and a policy-constrained case.

The solution algorithm of the EPPA model finds least-cost reductions for each gas in each sector and if emissions trading is allowed it equilibrates the prices among sectors and gases (using GWP weights). This set of conditions, often referred to as "what" and "where" flexibility, will tend to lead to least-cost abatement. Without these conditions abatement costs will vary among sources and that will affect the estimated welfare cost—abatement will be least-cost within a sector or region or for a specific gas, but will not be equilibrated among them.

The results depend on a number of aspects of model structure and particular input assumptions that greatly simplify the representation of economic structure and decision-making. For example, the difficulty of achieving any emissions path is influenced by assumptions about population and productivity growth that underlie the no-policy reference case. The simulations also embody a particular representation of the structure of the economy, including the relative ease of substitution among the inputs to production and the behavior of consumers in the face of changing prices of fuels, electricity and other goods and services. Further critical assumptions must be made about the cost and performance of new technologies and what might limit their market penetration. Alternatives to conventional technologies in the electric sector and in transportation are particularly significant. Finally, the EPPA model draws heavily on neoclassical economic theory. While this underpinning is a strength in some regards, the model fails to capture economic rigidities that could lead to unemployment or misallocation of resources nor does it capture regulatory and policy details that can be important in regulated sectors such as power generation.

I use EPPA to compare shadow prices (i.e., carbon prices) with and without REDD under emission constraints and different trading scenarios.

4.2 Emission Targets

The compliance period for the Kyoto Protocol commitments is 2008 through 2012. Since REDD market entry is not foreseeable during the Kyoto Protocol compliance period, I assume that REDD credits will be available as part of an emission trading scheme under a post-Kyoto agreement. To model REDD, this requires assuming hypothetical emission commitments for all participating regions as targets are not finalized. Based on the 2009 G8 Summit talks and CLEAR (Carbon Limits + Early Action = Rewards) Target (Wagner et al., 2009), I assume the following targets.

	US	OECD Europe	Russia	Canada, Japan, Rest of OECD Pacific	Rest of E. Europe/Eurasia	Developing Countries
2020	-17%	-20%	-10%	10%	-10%	BAU until 2018
2050	-80%	-80%	-80%	-80%	-50%	-30%

* % difference from 1990 levels

Conceptually, CLEAR targets, also known as Clean Investment Budgets, represent the idea that emerging economies adopt targets that are initially above current levels but within the *2 degree Celsius* global goal[2]; this provides immediate availability of allowances for industrialized nations while providing funding for emerging economies to transition to a low-carbon economy (Wagner et al., 2009). In the 2009 G8 Summit in L'Aquila Italy, G8 countries have committed to reduce their GHG emissions by 80% by 2050 from 1990 levels, and other major emitting countries have agreed to reduce their emissions by 50% by 2050 (G8 Summit Papers, 2009). For developing countries, I modeled a stringent scenario where they reach a 30 percent reduction below their respective 1990 levels by 2050, with reductions starting in 2019. These developing countries include the REDD supplying regions. All emission targets are assumed to decline linearly.

4.3 Reference 'No REDD' Case

Emissions trading allow participating nations to reduce emissions cost-effectively. In addition, carbon offsets come in many forms. Therefore, the effects of REDD trading needs to be isolated

[2] Agreement to keep mean global temperature within 2 degrees Celsius above pre-industrial level

from non-REDD offsets (i.e., trading emissions reductions in industrial sectors) to understand the sole effect of REDD credits. I designate the trading scenario without REDD as the reference '*No REDD*' case, which is modeled as the emissions targets described above with full global emissions trading allowed. The REDD allowances are then added to the resulting emissions from the '*No REDD*' case, and these new emissions are imposed as the new emission caps. This allows REDD offsets to be isolated from other allowances and other non-REDD offsets. Therefore, REDD trading occurs ex post the reference case, where all other offset and allowances are traded prior to REDD entering the market. These revised emission targets are added as a constraint in EPPA and are used for all scenarios for comparison purposes.

4.4 REDD Supply

I use marginal cost estimates to capture the potential supply of REDD. The marginal cost curves relate the opportunity costs of REDD to the amount of emissions reduced from REDD-activities; these costs include the forgone profits from reduced deforestation in sectors such as agricultural, or forestry products, as well as administrative costs to cover forest management.

I use an amended MAC curve based on estimates from the Global Timber Model (GTM). The Global Timber Model[3] is a partial equilibrium intertemporal optimization economic model that maximizes welfare across 250 world timber supply regions through the management of forest stand ages, compositions, and acreage given production and land rental costs. The model simulates trade responses to policy by predicting supply responses to current and future prices (EPA Analysis of H.R. 2454, 2010). The model assumes that all international mitigation practices are eligible from 2010 to 2050, and that mitigation activity is disaggregated into afforestation, forest management, and avoided deforestation. The model estimates the aggregated international forestry marginal abatement costs (EPA Analysis of H.R. 2454, 2010). Using estimated shares of total forest carbon mitigation attributed to reduced deforestation from Murray et al. (2009), the MAC is adjusted to reflect mitigation from reduced deforestation activities (Figure 4).

Typically we would just equate the REDD supply and regional MAC curves to determine the cost-effective allocation of REDD. However, REDD is not implemented endogenously in EPPA and cannot represent REDD MAC curves explicitly. I allocate a fixed supply of REDD allowances over time, based on the MAC curve in Figure 4. For the base case, I use the maximum available REDD in each year, which I define as the level at which costs turn vertical - as noted by the circles in Figure 4.

[3] Developed by Brent Sohngen from the Department of Agricultural, Environmental, and Developmental Economics (Ohio State University) with collaboration from Robert Mendlesohn, Roger Sedjo, and Kenneth Lyon

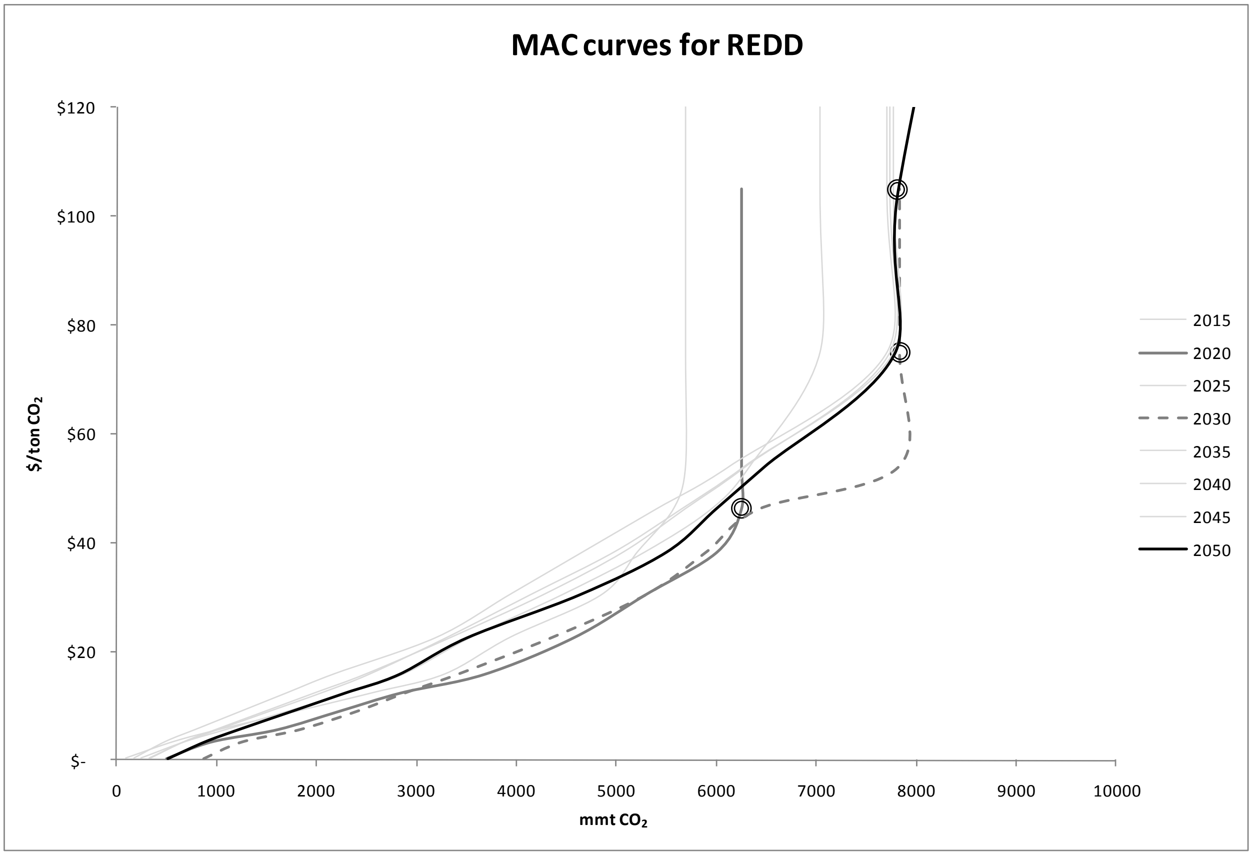

Figure 4. Global Avoided Deforestation Costs

These estimates are based on a global assessment. Since EPPA is a multi-region CGE model, these estimates need to be disaggregated regionally. I use estimates from three forestry and land-use models from Kindermann et al. (2008):

(1) Dynamic Integrated Model of Forestry and Alternative Land Use (DIMA): assesses land-use options in agriculture and forestry across the globe. The model predicts deforestation in forests where land values are greater in agriculture than in forestry, and vice versa, afforestation of agricultural and grazing lands where forestry values exceed agricultural ones.
(2) Generalized Comprehensive Mitigation Assessment Process Model (GCOMAP): a dynamic partial equilibrium model that analyzes afforestation in short- and long-run species and reductions in deforestation in 10 world regions.
(3) Global Timber Model (GTM): dynamic optimization model that optimizes the land area, age class distribution, and management of forestlands in 250 timber types globally. (Kindermann et al., 2008)

Each model has model-specific assumptions about the future of agricultural land rents, demand for forestry products, technological change, and other economic drivers; the models provide future deforestation projections and the resulting emissions of carbon into the atmosphere (Kindermann et al., 2008). The three models estimate the costs for avoiding tropical deforestation globally and for the three major tropical deforestation regions: Central and South

America, Africa, and Southeast Asia (Figure 5). I use these MAC curves to estimate the reduction contribution by region. As above, I assume the maximum available credits are where costs go vertical; since I only use these MAC curves to estimate the regional contributions, I aggregate the estimates between models and years and assume that the percent contribution by region remains constant. I use the calculated regional contribution estimates to regionally disaggregate the global REDD credits shown in Figure 4.

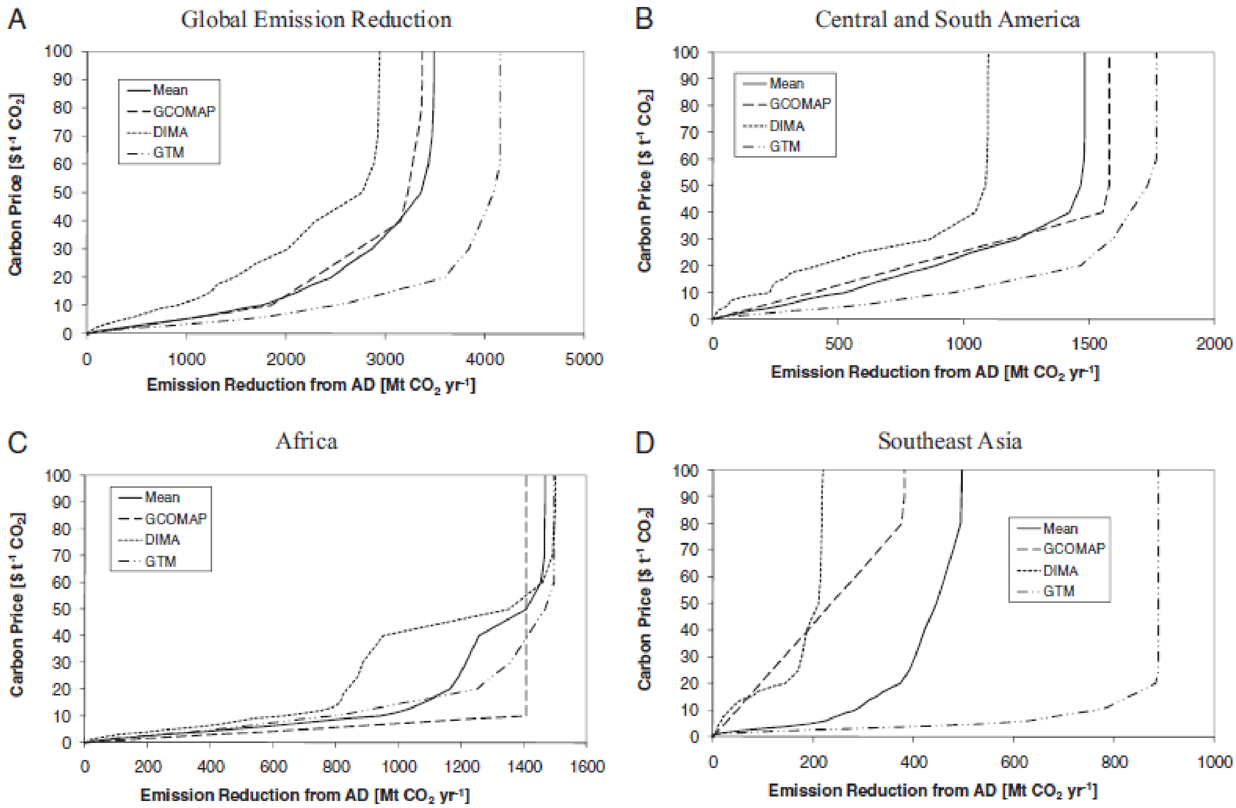

Figure 5. Marginal Costs of emission reductions from avoided deforestation activities in 2020 in three regions from three models (Kindermann et al., 2008)

Because EPPA does not model REDD endogenously, I model these regional REDD credits as additional allowances allocations to the supplying region. For example, suppose Central & South America's (LAM) reference emission targets are 1000mmt C. If LAM has 30mmt C available REDD credits, then I raise LAM's carbon quota to 1030mmt C; therefore, LAM has 30mmt C additional allowances that it can trade with its trading partners. In addition, for Southeast Asia, I assumed that all REDD activities occurs in Indonesia for accounting simplicity, since regions in Southeast Asia are not aggregated.

4.5 Demand Restrictions

In the proposed American Clean Energy and Security Act of 2009 (H.R. 2454, Waxman-Markey Bill), there is a carbon offset restriction of 2 billion metric tons CO_2 (bmt CO_2), where 1 bmt CO_2 offsets are limited to domestic sources and the remainder limits the international offsets available. If there are insufficient domestic offsets available, up to 1.5 bmt CO_2 can be obtained internationally. After 2017, international offsets are discounted; for every 1.25 international offset acquired, only one offset is credited. For this analysis, I assume that the US can only acquire 1bmt CO_2 of REDD offsets for all years for my analysis. I only focus on demand restrictions from the US due to computational limitations.

Since REDD is modeled as additional emission allowance and is available for all trading partners, the allocation of REDD is the only exogenous constraint on the quantity of REDD acquired by the US. Therefore, to model the US 1bmt CO_2 international offset restriction, I implemented and iterative-algorithm (in Matlab) to determine the correct REDD allocation such that US acquires 1bmt CO_2 REDD offsets. The methodology is as follows:

1. Start with an initial guess for the starting REDD allocation
2. Call EPPA to run the scenario of interest with the starting REDD allocation.
3. Compare US emissions levels from EPPA to US emissions with 1bmt CO_2 REDD offsets (US reference case emissions + 1bmt CO_2)
4. If they diverge, recalculate a new REDD allocation to input into EPPA
5. Repeat until convergence in step 4
   Convergence is defined to be where emissions are within 3E-5 of each other.

A limitation of using this approach to model demand constraints is that additional demand constraints from other regions over-constrains the problem thus making solution is indeterminate. Therefore, I only focus on US demand restrictions for this study. Since this method is computationally intensive, I only investigated the two extreme trading scenarios: *US-only* and *All Regions*.

4.6 Cost Uncertainties

To observe cost-containment behavior, cost uncertainties need to be simulated. I apply assumptions from Webster et al. (2008b), which identified 110 parameters in the EPPA model that affect emissions growth and abatement costs. These include parameters representing labor productivity growth rates, energy efficiency trends, elasticities of substitution, cost of advanced technologies, fossil fuel resource availability, and urban pollutant trends (Webster et al., 2008b). Probability distributions for these parameters were developed based on historical data and expert judgment.

Here, I perform Monte Carlo simulation using Latin Hypercube sampling with 400 samples drawn from each of the parameter distributions. These samples are input into the EPPA model to generate cost uncertainties. I compare the carbon prices with and without REDD under different trading scenarios and US offset restrictions to determine if REDD exhibits cost containing behavior and if trading scenarios and offset demand restriction limit cost-containing behavior.

4.7 REDD Supply Uncertainties

There are underlying uncertainties in the REDD supply estimates, primarily from uncertainties in opportunity costs estimates and deployment estimates. Since opportunity costs consist of forgone profits from deforestation-related activities, they are influenced by agricultural prices and other market prices, which, like all markets, are subjected to uncertainties. In addition, deployment of these credits depends on a country's readiness level to enter the market, which can be due to access to monitoring and operating forest management system. While there are efforts from the

Bali Action Plan to encourage REDD-readiness activities, there is no certainty as to how much REDD will actually be available in the emissions trading scheme.

Using high to low opportunity cost scenarios based on fast to slow deployment scenarios, I construct probability distributions representing supply uncertainties. The deployment scenarios are as follows:

DEPLOYMENT	REGIONS: Central & S. America	Africa	SE Asia
Slow	10% credits in 2013 rest phased over 2013-2022	phased in over 15 yrs (2031-2045)	phased in over 15 yrs (2021-2035)
Medium	30% credits in 2013 rest phased over 2013-2022	phased in over 15 yrs (2026-2040)	phased in over 15 yrs (2016-2030)
Fast	50% credits in 2013 rest phased over 2013-2017	phased in over 10 yrs (2026-2035)	phased in over 10 yrs (2016-2025)

The three opportunity cost scenarios as based on the three forestry and land use models from Section 4.4. High opportunity costs use estimates from DIMA; medium opportunity costs are scaled to the GCOMAP model, and low opportunity costs are scaled to GTM model estimates, see Figure 5. Probability distributions are fit around these scenarios, with the following probability assumptions:

<u>Deployment:</u>
Fast: 25% probability
Medium: 50% probability
Slow: 25% probability

<u>Opportunity Cost:</u>
High: 25% probability
Medium: 50% probability
Low: 25% probability

I use these scenarios to construct two alternative probability distributions for supply uncertainty: (1) combined deployment and opportunity cost uncertainties; and (2) opportunity cost uncertainties with fast deployment. Using Monte Carlo simulation, 400 samples are drawn from each supply distribution and modeled into EPPA to simulate supply uncertainties. These are incorporated into EPPA and modeled with REDD offsets to determine the effect of supply uncertainties on the cost-containment effectiveness of REDD.

5. **Results**

I analyzed REDD offsets deterministically and stochastically. The deterministic results illustrate the effect of REDD offsets on expected costs. The stochastic analysis assesses the effects of REDD on carbon price uncertainty, which is the central to understand whether REDD reduces upside risk through cost-containment. As mentioned in Chapter 4, I analyze two demand and supply scenarios to assess the effect of increased scarcity of REDD on carbon price. The demand scenarios examine the effect of (1) competition over demand for REDD as seen by increasing the number of regions that can purchase REDD, and (2) limitations on the number of REDD credits a region can purchase. Supply scenarios are based on opportunity cost uncertainties of REDD based on a range of deployment rates.

In Section 5.1, I present the results of the deterministic scenario analysis. Section 5.2 presents Monte Carlo results of REDD without supply uncertainties, both Section 5.1 and 5.2 assume no restriction on offset purchases. Section 5.3 presents the results of the US restriction on offsets purchases using deterministic and Monte Carlo analysis. Section 5.4 presents Monte Carlo results with supply uncertainties. Lastly, Section 5.5 presents the results of the special scenario where China is allowed to purchase REDD offsets with Annex I regions; this scenario is analyzed both deterministically and stochastically.

5.1 Deterministic Results

In this section, I show results for the three main trading scenarios, defined in terms of the regions that can purchase REDD offsets: (1) *US-only*; (2) *Annex I*; (3) *All Regions*. I discuss results for the scenario that allows Annex I and China to purchase REDD in Section 5.5 below as it exhibits unique dynamics. Deterministic analysis of REDD credits show that REDD credits lower expected compliance costs for all three scenarios, as shown in Figure 6; Table 2 summarizes the carbon prices and relative cost savings from REDD by year and trading scenario.

Increasing competition via increasing the number of REDD buyers plays a significant role in reducing the expected savings from including REDD. The largest carbon price reduction occurs when US is the only region that purchases REDD as they have access to the entire global supply of REDD. The *US-only* scenario reduces expected carbon prices by 75% in 2040 and 54% in 2050. As more regions are allowed to purchase REDD, the effect of REDD on carbon price is diminished as each region purchases fewer allowances due to increased competition in demand. In the *US-only* and *Annex I* scenarios, the surplus of REDD allowances generates carbon leakage, as indicated by US emissions exceeding emissions under the 'No Policy' (BAU) scenario (Figure 6). However, even under the most competitive scenario, *All Regions*, there is still a 41% reduction in expected costs, which is substantial.

In later years, REDD has a diminished effect in reducing costs as emission targets become more stringent; the relative quantity of REDD allowances, with respect to required emissions abatement, decreases over time. Also, the effect of competition over demand also decreases over time (Figure 6). This is evident by the carbon price gap between the *Annex I* and *All Regions* scenarios decreasing significantly in later years, most notably in 2050. In addition, the difference in US emissions between the *Annex I* and *All Regions* scenarios is reduced in the years 2040 through 2050. In these years, several regions, most notably China and the Middle East regions, purchase fewer REDD offsets under the *All Regions* scenario thus allowing the US and other Annex I nations to purchase more REDD thereby reducing the difference in emissions in Annex I regions for the *Annex I* and *All Regions* scenarios, as observed in US emissions in Figure 6. These trading dynamics generate more cost savings for the *All Regions* scenario for 2040 through 2050 thus reducing the carbon price difference between *Annex I* and *All Regions*.

	Carbon Price, \$/tCO_2				% Reduction from No REDD		
	No REDD	US-only	Annex I	All Regions	US-only	Annex I	All Regions
2020	$32	$0	$0	$4	100%	100%	86%
2025	$64	$0	$0	$24	100%	100%	62%
2030	$84	$0	$14	$47	100%	83%	44%
2035	$102	$0	$40	$68	100%	61%	34%
2040	$137	$34	$72	$83	75%	47%	39%
2045	$162	$65	$99	$109	60%	39%	32%
2050	$228	$105	$132	$134	54%	42%	41%

Table 2. Carbon Prices for different trading scenarios and percent reduction from 'No REDD' Reference Case

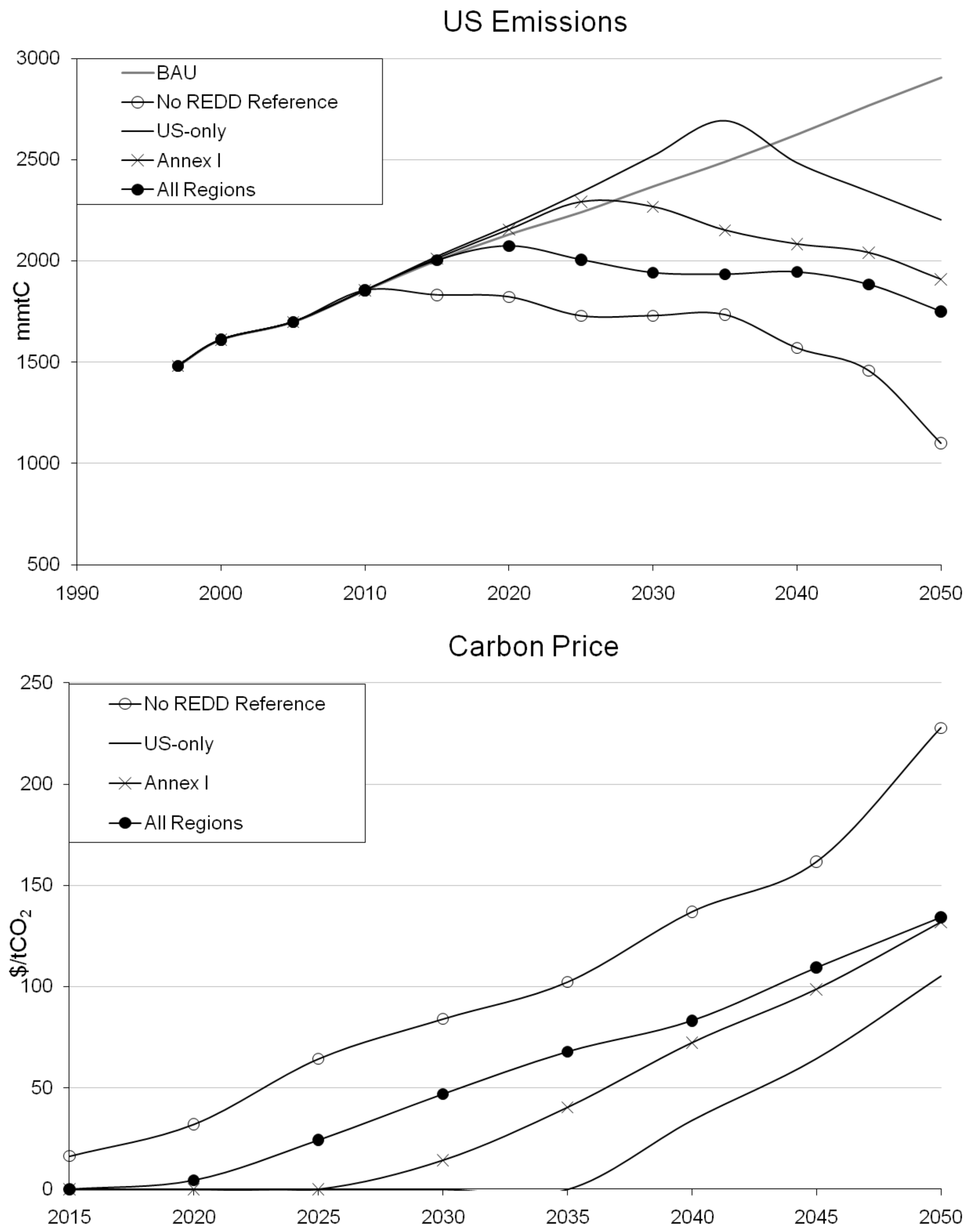

Figure 6. US Emissions and Carbon Prices under three REDD Trading Scenarios

5.2 Stochastic Simulation Results

In this section, I present Monte Carlo simulation results using the 400 cost and emissions uncertainty samples on the same three major trading scenarios from Section 5.1 above. Monte Carlo results of REDD show that REDD credits reduce carbon prices at the median, 95th and 99th percentile of the carbon price distribution (Tables 3, 4, and 5, Figure 7).

In general, the costs at the median of the carbon price distribution (Table 3) are similar to the expected costs from deterministic results (Table 2). There are some minor differences in later years, where expected costs are slightly higher than median costs; these differences show that the carbon price distribution is slightly skewed. The relative reductions in costs, as a percentage of *No REDD* costs, are similar for costs at the 95th/99th percentile, expected and median, with some differences in later years. The carbon prices at the upper tail of the distribution (at the 95th and 99th percentile) show slightly higher relative reductions than median and expected carbon prices. Although relative reductions are comparatively consistent between expected costs, median costs and costs at the upper tail end of the distribution, the actual reductions in carbon price are greater in the tails since the costs are highest at the tails (Table 4 and 5).

As in the deterministic results, the effect of competition over demand plays a significant role on carbon prices, as seen in 2030 in Figure 8. Similarly, these effects diminish in later years as targets get more stringent in later years; this restricts demand more than from increased competition. In 2040 and 2050, US purchases larger amounts of REDD under the *US-only* and *All Regions* scenario compared to 2030; however these larger amounts do not translate into substantial cost savings as seen in earlier years thus confirming the effect of more stringent targets (Figure 8).

As in deterministic analysis, REDD and increasing competition over demand for REDD have a diminished effect over costs in the later years; *Annex I* and *All Regions* trading scenarios exhibit similar behaviors as in deterministic scenarios, where differences between these two cases decrease and almost disappear by 2050. This effect is stronger at the tails of the distribution, where the differences in cost between the *Annex I* and *All Regions* scenarios are smaller at the tails than at the median during these later years (Table 4 and 5). Moreover, in 2050, the differences between *US-only* with *Annex I* and *All Regions* scenarios are noticeable reduced, especially at the tails of the distribution (Figure 7 and 8).

Therefore, deterministic and Monte Carlo results show that REDD credits reduce expected costs and reduce median and tail end costs thus containing costs under cost uncertainty. Monte Carlo results show that relative cost savings at median and upper tail end of the carbon price distribution, are relatively consistent by percentage of *No REDD* costs; therefore, actual cost savings at the upper tail of the carbon price distribution are substantially higher than at the median or expected values. Hence, REDD credits yield larger cost savings during high costs than at lower costs. Competition over demand plays a significant role in the early years, as increasing buyers reduces cost savings from REDD. However, since emission targets are more stringent in later years, the competition effect over demand is significantly diminished as targets are more limiting on demand over REDD.

		Carbon Price, $/tCO$_2$				% Reduction from No REDD		
		No REDD	US-only	Annex I	All Regions	US-only	Annex I	All Regions
MEDIAN	2020	$31	$0	$0	$4	100%	100%	86%
	2025	$62	$0	$1	$23	100%	98%	63%
	2030	$83	$0	$15	$42	100%	82%	50%
	2035	$103	$2	$39	$60	98%	62%	42%
	2040	$133	$30	$69	$80	78%	48%	40%
	2045	$160	$60	$92	$98	62%	43%	39%
	2050	$217	$91	$116	$123	58%	47%	44%

Table 3. Median Carbon Prices for different trading scenarios and percent reduction from 'No REDD' Reference Case

		Carbon Price, $/tCO$_2$				% Reduction from No REDD		
		No REDD	US-only	Annex I	All Regions	US-only	Annex I	All Regions
95th Percentile	2020	$45	$0	$0	$9	100%	100%	81%
	2025	$86	$0	$12	$36	100%	86%	57%
	2030	$115	$0	$35	$65	100%	70%	43%
	2035	$145	$24	$71	$90	83%	51%	38%
	2040	$181	$66	$115	$122	64%	37%	33%
	2045	$228	$114	$145	$142	50%	37%	38%
	2050	$344	$163	$183	$176	53%	47%	49%

Table 4. Carbon Prices at the 95th percentile for different trading scenarios and percent reduction from 'No REDD' Reference Case

		Carbon Price, $/tCO$_2$				% Reduction from No REDD		
		No REDD	US-only	Annex I	All Regions	US-only	Annex I	All Regions
99th Percentile	2020	$54	$0	$0	$11	100%	100%	80%
	2025	$99	$0	$17	$45	100%	83%	54%
	2030	$132	$5	$43	$79	96%	68%	41%
	2035	$159	$37	$90	$103	77%	44%	36%
	2040	$201	$86	$131	$138	57%	35%	31%
	2045	$256	$149	$177	$161	42%	31%	37%
	2050	$433	$188	$215	$212	57%	50%	51%

Table 5. Carbon Prices at the 99th percentile for different trading scenarios and percent reduction from 'No REDD' Reference Case

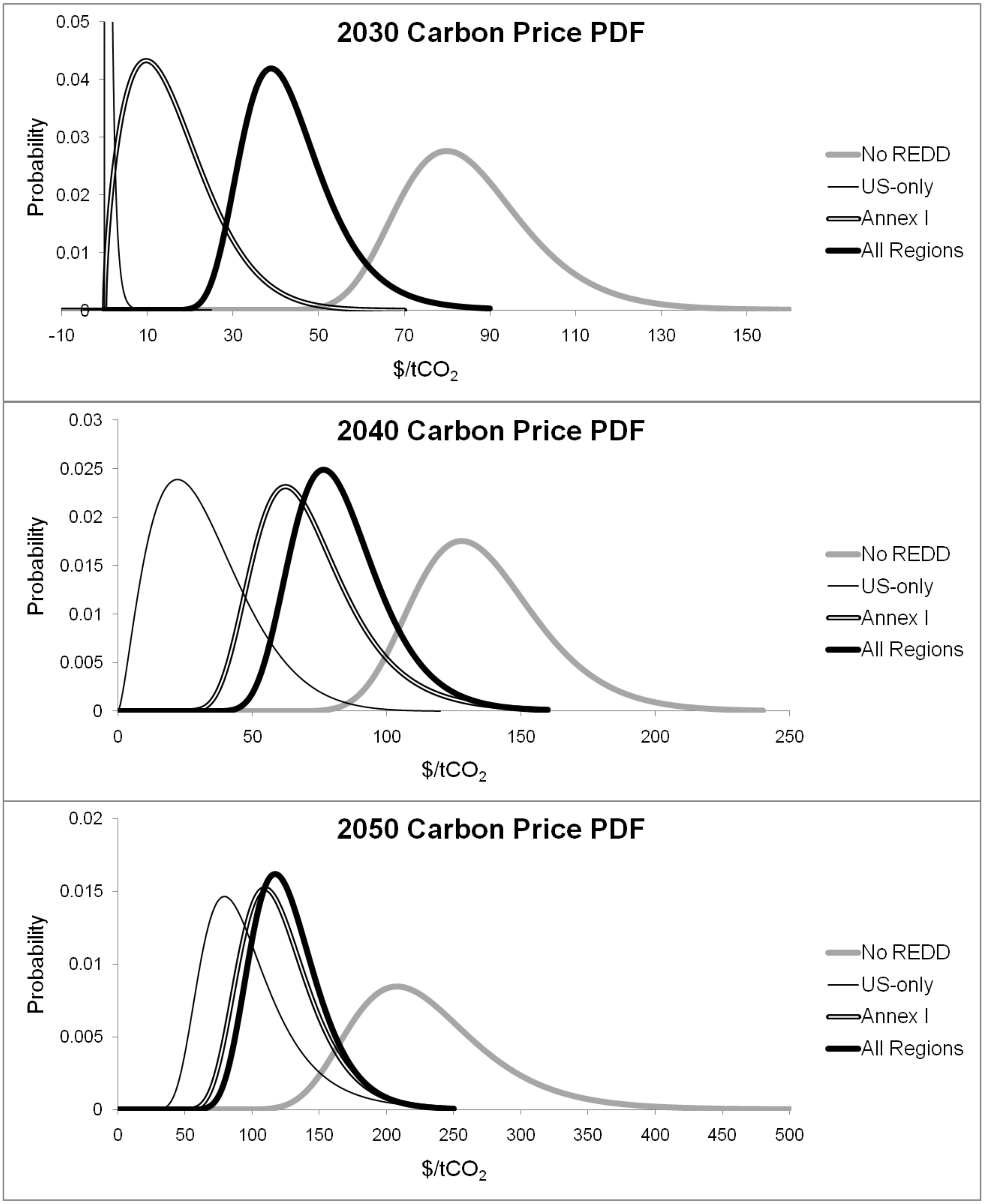

Figure 7. Carbon Price Distribution for 2030, 2040, 2050

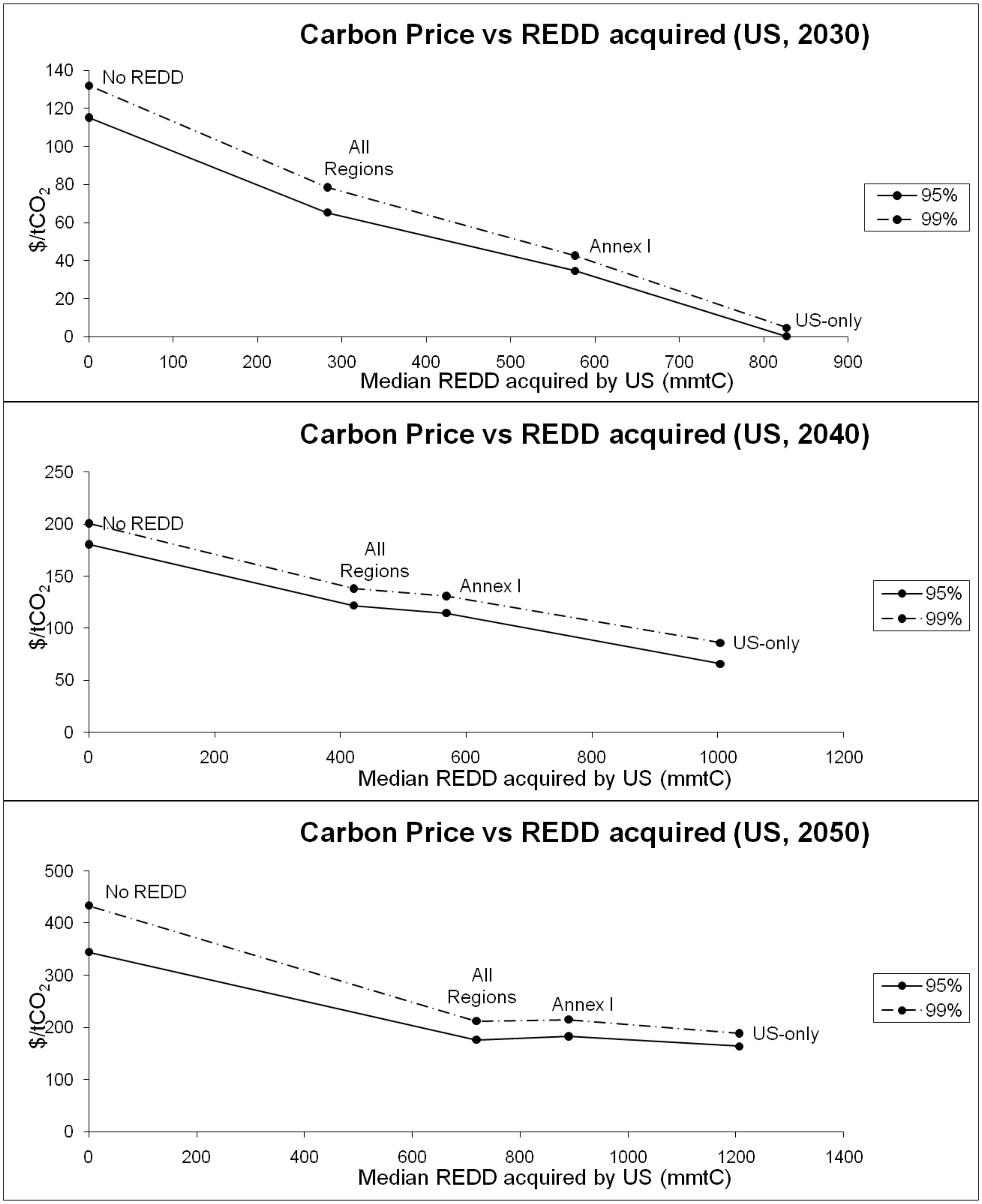

Figure 8. Carbon Price vs. Median REDD Acquired by US in 2030, 2040, and 2050

5.3 Demand Restrictions

In this section, I discuss deterministic and Monte Carlo results from adding an additional restriction to the US where international offsets purchased in any year cannot exceed 1bmt CO_2. In this section, I restrict my analysis to two trading scenarios: (1) *US-only* and (2) *All Regions*. In all results, the US is the only region with imposed restrictions on purchasing offsets.

5.3.1 Deterministic Results

The results of adding this restriction under emissions and cost certainty show that demand restrictions reduce the effectiveness of REDD in reducing compliance costs, as shown in Figure 9. The reductions in cost savings from the demand restriction increase over time as shown in Table 6 and Figure 9. The carbon price under both restricted scenarios rises above that of the unrestricted *All Regions* scenario. Thus, demand restrictions reduce the costs savings from REDD more than does increased competition. Note that the differences in carbon prices between the two restricted trading scenarios are small compared to the unrestricted case for the same two trading scenarios; therefore, demand restrictions weaken competition effects as these demand restrictions are more limiting on the demand over REDD credits. In general, the *All Regions* scenario reduces costs a little more than the *US-only* scenario since the *All Regions* scenario allows other regions to purchase offsets without affecting US demand for REDD thus capturing cheaper abatement opportunities that did not exist in *US-only* scenario, with exception of a few years, 2020, 2030, and 2035. During these years, the global supply of REDD offsets needed for the US to purchase 1bmt CO_2 is greater than the assumed maximum supply for that given year; therefore, US emissions are lower and carbon prices are higher in the *All Regions* than in the *US-only* scenario during those years.

	Carbon Price, $/tCO$_2$					% Reduction from No REDD			
	No REDD	US-only	US-only (R)	All Regions	All Regions (R)	US-only	US-only (R)	All Regions	All Regions (R)
2020	$32	$0	$4	$4	$3	100%	87%	86%	92%
2025	$64	$0	$30	$24	$23	100%	54%	62%	65%
2030	$84	$0	$45	$47	$45	100%	47%	44%	47%
2035	$102	$0	$59	$68	$67	100%	42%	34%	35%
2040	$137	$34	$119	$83	$109	75%	13%	39%	21%
2045	$162	$65	$141	$109	$133	60%	13%	32%	18%
2050	$228	$105	$202	$134	$196	54%	11%	41%	14%

Table 6. Percent Carbon Price Reduction under Demand Restrictions (R denotes US demand restriction)

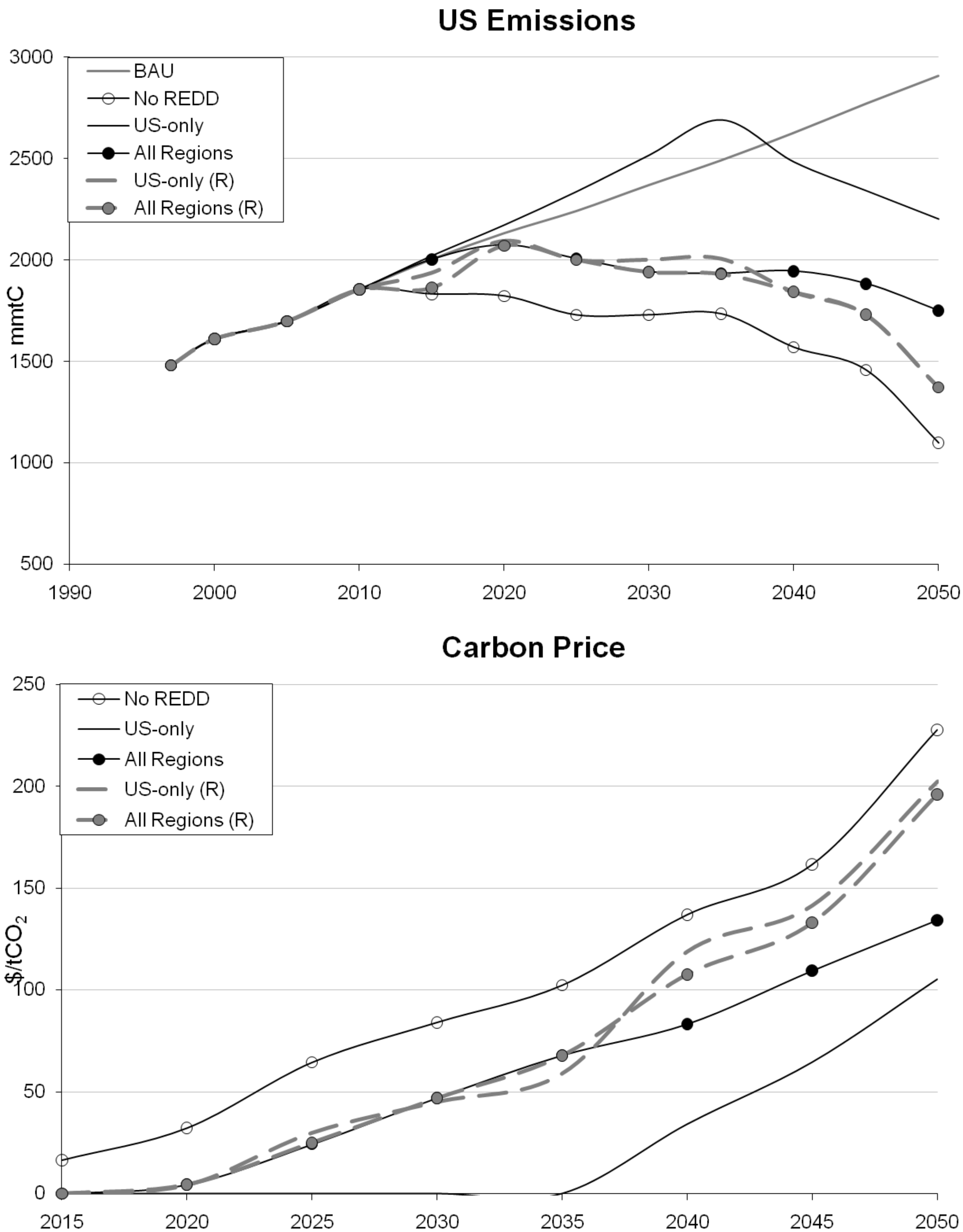

Figure 9. US Emissions and Carbon Price under US Demand Restrictions (Deterministic)

5.32 Stochastic Simulation Results

As in the deterministic results, US demand restrictions significantly reduce the cost savings from REDD for all years. Carbon price distributions for the restricted *US-only* scenario start overlapping the distribution from the unrestricted *All Regions* scenario in early years and shifts further right (towards increasing carbon price) (Figure 10). As in deterministic results, costs under both restricted *US-only* and restricted *All Regions* scenario are higher than costs under the unrestricted *All Regions* scenario at the median and at the tails of the carbon price distribution (Tables 7, 8, and 9).

In general, the US offset restriction slightly skews the carbon price distribution slightly to the right, except for 2040. This effect is more pronounced for the restricted *US-only* scenario. The restricted *All Regions* scenario shows no skew for 2035 and 2040. Similar to deterministic results, the restricted *All Regions* scenario generally has lower costs than the restricted *US-only* scenario.

Note that even though we establish a 'No REDD' reference, the trade of additional non-REDD offsets is unavoidable based on the current exogenous implementation of offsets in EPA. Therefore, there are residual non-REDD (i.e., industrial emission reduction) allowances traded, but these remain small compared to REDD. However, this effect is pronounced for the restricted scenarios at the 99th percentile for 2045 and 2050, where costs exceed the *No REDD* case. For the restricted *US-only* scenario, during these last years, extreme high costs at the tail end cause REDD supplying regions, especially Central and South America and Africa, to trade non-REDD offsets, in addition to REDD offsets; as a result, emissions to drop below *No REDD* reference emissions for these REDD supplying regions thus raising costs for these later years. Moreover, during these years, the costs from restricted *All Regions* scenario exceed the costs from the restricted *US-only* scenario at the upper tail end of the distribution thereby further exceeding *No REDD* costs. These higher costs at the tail end of the distribution for the restricted *All Regions* scenario is a result of emission trading dynamics; some regions, particularly Europe, the Former Soviet Union, Japan and China, take on significant emission reductions compared to the restricted *US-only* scenario. Since most of these regions tend to have high marginal abatement costs, these emission reductions drive carbon prices higher for the restricted *All Regions* scenario.

Therefore, REDD demand restrictions may provide some relief for price shocks for early years; however, cost savings are substantially reduced even exceeding the most competitive trading scenario, *All Regions*, under the case of no purchasing restrictions. In later years, 2045-2050, these restrictions can effectively render REDD ineffective at reducing carbon price uncertainty.

		Carbon Price, $/tCO$_2$					% Reduction from No REDD			
		No REDD	US-only	US-only (R)	All Regions	All Regions (R)	US-only	US-only (R)	All Regions	All Regions (R)
MEDIAN	2020	$31	$0	$5	$4	$4	100%	84%	86%	87%
	2025	$62	$0	$29	$23	$26	100%	54%	63%	58%
	2030	$83	$0	$49	$42	$45	100%	41%	50%	45%
	2035	$103	$2	$72	$60	$68	98%	30%	42%	34%
	2040	$133	$30	$108	$80	$104	78%	18%	40%	22%
	2045	$160	$60	$142	$98	$138	62%	12%	39%	14%
	2050	$217	$91	$200	$123	$205	58%	8%	44%	6%

Table 7. Median Carbon Prices for different trading scenarios and percent reduction from 'No REDD' Reference Case (Demand Restriction)

		Carbon Price, $/tCO$_2$					% Reduction from No REDD			
		No REDD	US-only	US-only (R)	All Regions	All Regions (R)	US-only	US-only (R)	All Regions	All Regions (R)
95th Percentile	2020	$45	$0	$17	$9	$9	100%	62%	81%	79%
	2025	$86	$0	$46	$36	$42	100%	47%	57%	50%
	2030	$115	$0	$81	$65	$74	100%	30%	43%	36%
	2035	$145	$24	$113	$90	$109	83%	23%	38%	25%
	2040	$181	$66	$174	$122	$175	64%	4%	33%	3%
	2045	$228	$114	$246	$142	$256	50%	-8%	38%	-12%
	2050	$344	$163	$318	$176	$332	53%	8%	49%	4%

Table 8. Carbon Prices at 95th percentile for different trading scenarios and percent reduction from 'No REDD' Reference Case (Demand Restriction)

		Carbon Price, $/tCO$_2$					% Reduction from No REDD			
		No REDD	US-only	US-only (R)	All Regions	All Regions (R)	US-only	US-only (R)	All Regions	All Regions (R)
99th Percentile	2020	$54	$0	$22	$11	$18	100%	59%	80%	66%
	2025	$99	$0	$55	$45	$52	100%	45%	54%	48%
	2030	$132	$5	$93	$79	$86	96%	30%	41%	35%
	2035	$159	$37	$134	$103	$130	77%	16%	36%	18%
	2040	$201	$86	$203	$138	$205	57%	-1%	31%	-2%
	2045	$256	$149	$290	$161	$309	42%	-13%	37%	-21%
	2050	$433	$188	$457	$212	$473	57%	-5%	51%	-9%

Table 9. Carbon Prices at 99th percentile for different trading scenarios and percent reduction from 'No REDD' Reference Case (Demand Restriction)

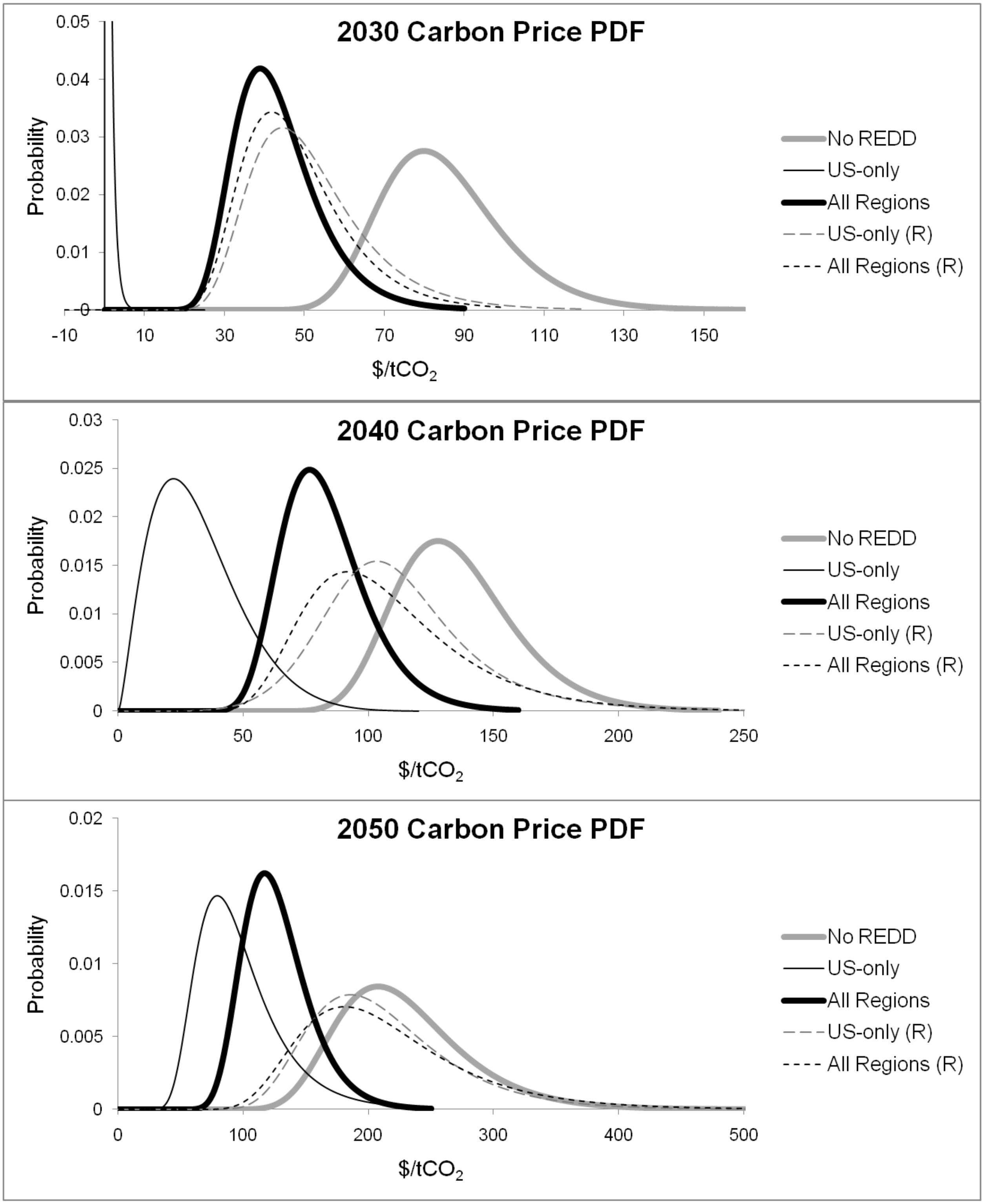

Figure 10. Carbon Price Distribution under US Demand Restrictions for 2030, 2040, 2050

5.4 Supply Uncertainty

In this section, I discuss Monte Carlo results from the two supply uncertainty scenarios: (1) combined and (2) fast deployment. The differences between these two supply scenarios are small but there are some slight differences in the early years, which diminish in later years. In the early years, the 'fast' scenario reduces carbon prices more than the 'combined' scenario since there is a greater probability of a larger REDD supply in the early years. After 2040, the differences between the combined and fast REDD supply scenarios are reduced; the more stringent targets are more restrictive than supply uncertainties. Since results for the two supply scenarios are similar, I focus on the combined opportunity cost and deployment uncertainty supply scenario results.

In general, the presence of opportunity cost and deployment uncertainties reduce the cost savings of REDD. For instance, in 2050, the reduction in carbon price for the *US*-only scenario at the median is 33%, compared to 58% without supply uncertainties (Table 10 and 3).

These supply uncertainties significantly impact the *US-only* scenario; in 2030, there is more variation in carbon prices compared to the base case with no supply uncertainties (Figure 7 and 11). This increase in carbon price variation for the *US*-only scenario in 2030 results in reduced cost savings at the tail of the distribution compared to the median (Table 10, 11, and 12). Contrary to the no supply uncertainty results, relative cost savings, as a percentage of *No* REDD costs, between the median and 95th and 99th percentile are not consistent; relative cost savings decreases at the upper tails of the distribution, where the *US-only* scenario is impacted the most due to the increase in carbon price variation. The addition of supply uncertainties further diminish the effects of competition over demand in later years, where stringent targets further increase REDD scarcity (Figure 11 and 12).

		Carbon Price, \$/tCO_2				% Reduction from No REDD		
		No REDD	US-only	Annex I	All Regions	US-only	Annex I	All Regions
MEDIAN	2020	$31	$14	$21	$24	53%	32%	22%
	2025	$62	$33	$44	$49	47%	29%	21%
	2030	$83	$42	$58	$65	49%	30%	22%
	2035	$103	$57	$73	$78	44%	29%	24%
	2040	$133	$80	$92	$100	40%	31%	25%
	2045	$160	$109	$114	$122	32%	29%	24%
	2050	$217	$146	$154	$167	33%	29%	23%

Table 10. Median Carbon Prices for different trading scenarios and percent reduction from 'No REDD' Reference Case (Combined Supply Uncertainty Scenario)

		Carbon Price, $\$/tCO_2$				% Reduction from No REDD		
		No REDD	US-only	Annex I	All Regions	US-only	Annex I	All Regions
95th Percentile	2020	$45	$26	$34	$37	43%	25%	19%
	2025	$86	$55	$65	$72	36%	24%	16%
	2030	$115	$76	$88	$93	34%	24%	19%
	2035	$145	$99	$112	$116	32%	23%	20%
	2040	$181	$132	$144	$145	27%	20%	20%
	2045	$228	$173	$173	$178	24%	24%	22%
	2050	$344	$233	$233	$248	32%	32%	28%

Table 11. Carbon Prices at 95th percentile for different trading scenarios and percent reduction from 'No REDD' Reference Case (Combined Supply Uncertainty Scenario)

		Carbon Price, $\$/tCO_2$				% Reduction from No REDD		
		No REDD	US-only	Annex I	All Regions	US-only	Annex I	All Regions
99th Percentile	2020	$54	$36	$42	$45	33%	22%	17%
	2025	$99	$71	$82	$86	29%	17%	14%
	2030	$132	$89	$106	$113	33%	20%	14%
	2035	$159	$115	$132	$133	28%	17%	17%
	2040	$201	$150	$154	$158	25%	23%	22%
	2045	$256	$200	$193	$196	22%	25%	23%
	2050	$433	$267	$280	$296	38%	35%	32%

Table 12. Carbon Prices at 99th percentile for different trading scenarios and percent reduction from 'No REDD' Reference Case (Combined Supply Uncertainty Scenario)

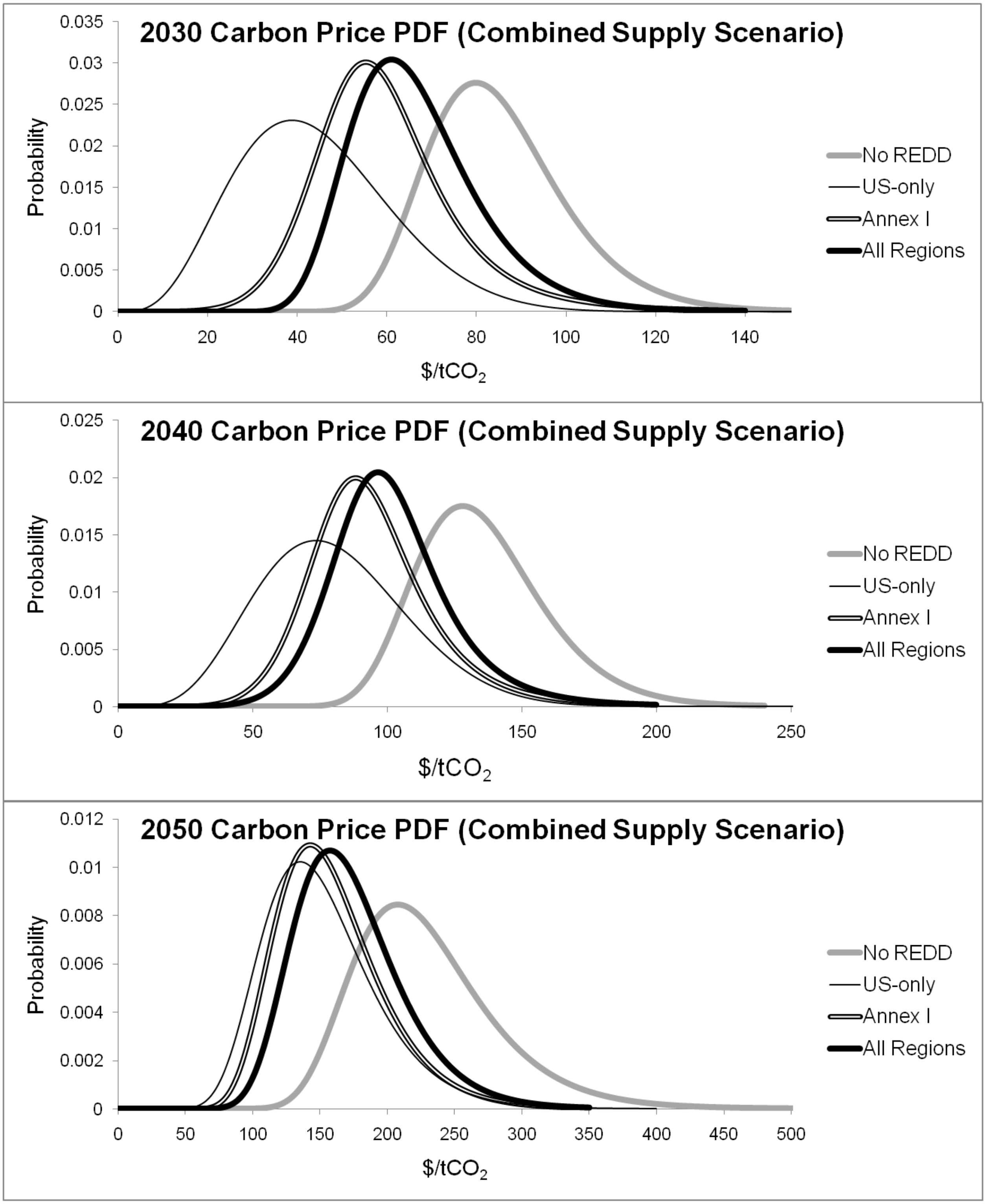

Figure 11. Carbon Price Distribution for Combined Supply Scenarios (2030, 2040, 2050)

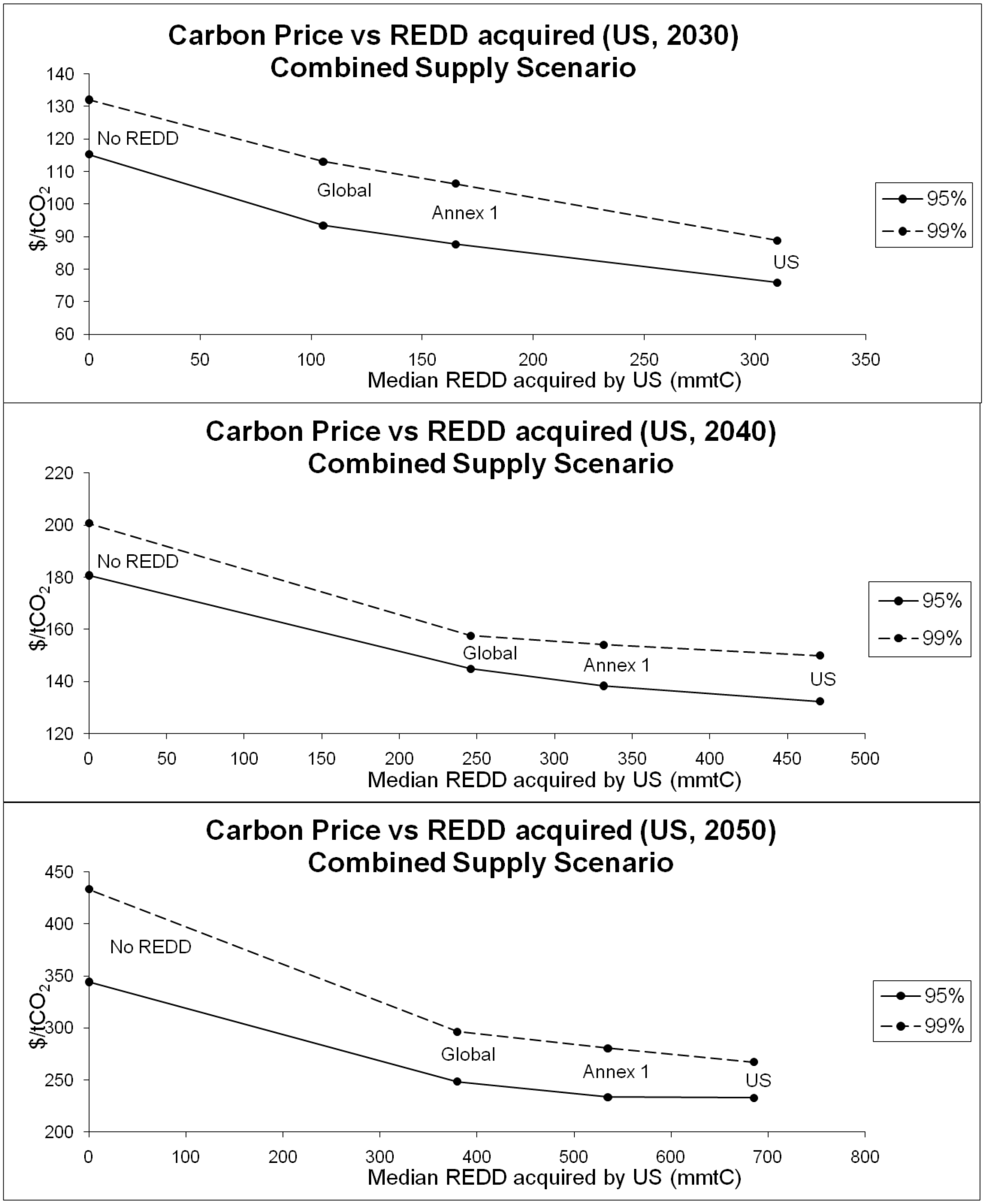

Figure 12. Carbon Price vs. Median REDD Acquired by US for Combined Supply Scenarios (2030, 2040, 2050)

5.5 The Addition of China

In this section, I present the results for the case where China can also purchase REDD allowances with Annex I regions. China compared to Annex I countries tends to have lower abatement costs compared to Annex I countries. Thus, the addition of only China presents an interesting scenario, where it can either compete for REDD allowance purchases or compete with REDD allowance sales.

5.51 Deterministic Results

As in the base case in Section 5.1, the deterministic results shows that, for the early years, increased competition over demand from allowing China to purchase REDD with Annex I regions reduces expected cost savings from REDD credits (Figure 13, Table 13). However, in the later years, the expected cost differences between *Annex I* and *Annex I & China* disappear, and in 2050, expected costs in the *Annex I & China* scenario is less than in the *Annex I* scenario (Figure 13). Moreover, during these later years, the difference in US emissions between *Annex I* and *Annex I & China* also disappear; therefore, US acquires similar amounts of REDD credits under both scenarios. In fact, after 2030, China starts to purchase fewer REDD credits, which allows Annex I countries to acquire more REDD (Figure 14). By 2050, China acquires 90% less REDD in 2050 compared to 2030, and US purchases more REDD in the *Annex I & China* scenario than *Annex 1* scenario (Figure 14), which explains why costs are lower with the addition of China.

	Carbon Price, $/tCO$_2$			% Reduction from No REDD		
	No REDD	Annex I	Annex I & China	US-only	Annex I	Annex I & China
2020	$32	$0	$0	100%	100%	100%
2025	$64	$0	$12	100%	100%	81%
2030	$84	$14	$33	100%	83%	61%
2035	$102	$40	$46	100%	61%	55%
2040	$137	$72	$72	75%	47%	47%
2045	$162	$99	$98	60%	39%	39%
2050	$228	$132	$128	54%	42%	44%

Table 13. Carbon Prices and percent reduction from 'No REDD' Reference Case (with the addition of China)

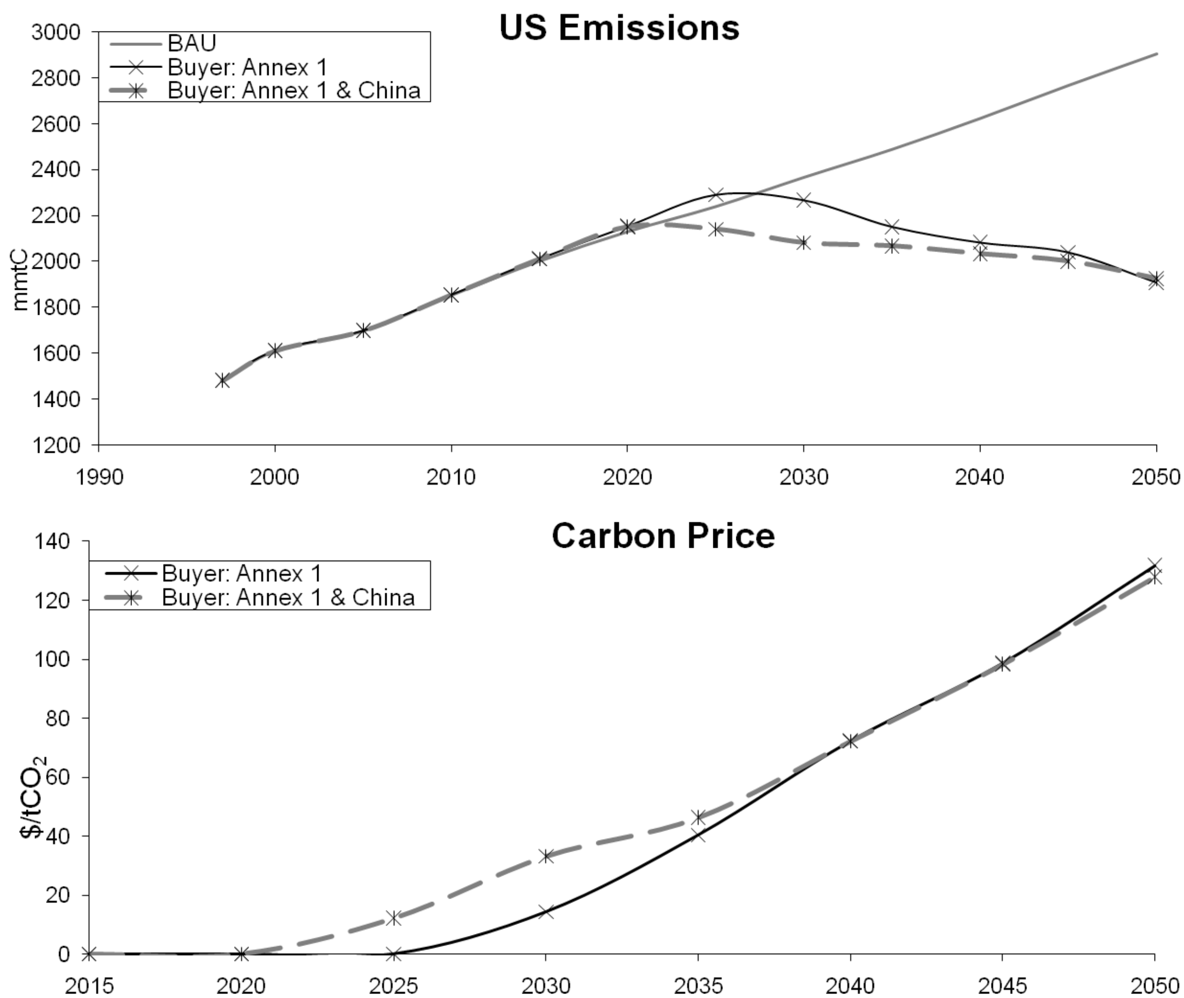

Figure 13. US Emissions and Carbon Price, China Effect (Deterministic)

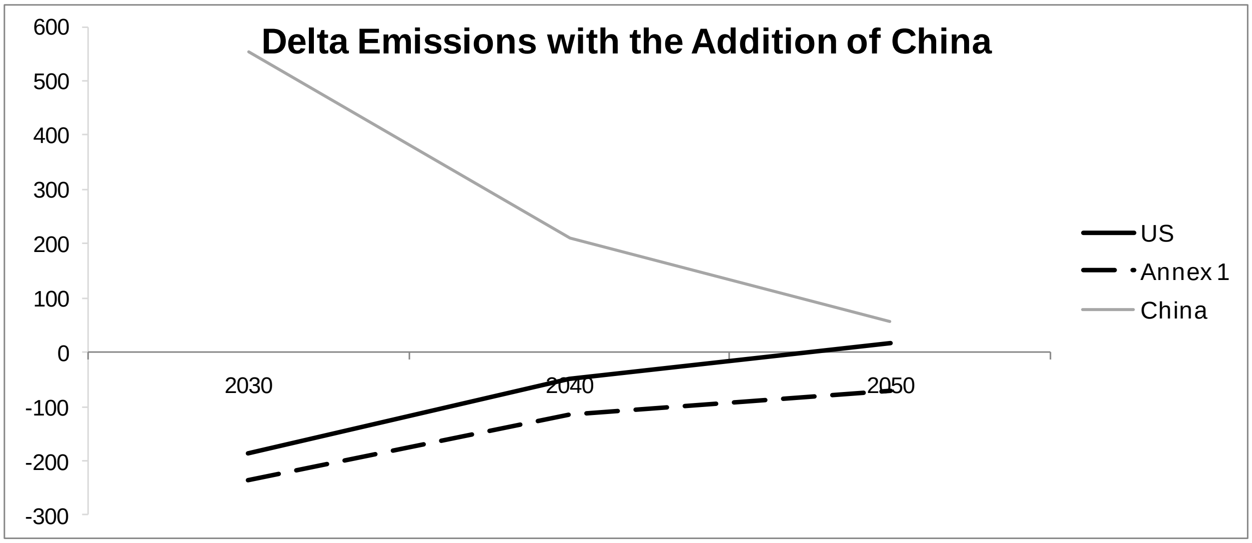

Figure 14. Emissions Difference between the Addition of China from Annex I alone

5.5.2 Stochastic Simulation Results

As in the deterministic analysis, Monte Carlo results of REDD for the scenario where China is allowed to purchase REDD with Annex I show a reduction in cost savings in the early years, and the differences between *Annex I* and *Annex I & China* scenarios diminish in later years (Tables 14, 15, 16, and Figure 15). Starting in 2045, median carbon prices for the *Annex I & China* scenario are lower than in the *Annex I* scenario; for the 95th and 99th percentile, this trend in carbon prices starts in 2040 (Table 15 and 16).

Based on deterministic results, Annex I nations start purchasing more REDD after 2040 since China gradually purchases less REDD offsets. In Monte Carlo results, these trading dynamics are more pronounced at the tail end of the carbon price distribution. Starting in 2040, the right tail of the carbon price distribution in the *Annex I & China* scenario is pulled in more than in the *Annex I* scenario (Figure 15), and carbon prices at the tails are lower for the *Annex I & China* scenario (Figure 16). Within Annex I and China regions, China is one of the countries with the lowest marginal abatement costs. Stringent emission targets in later years cause China purchase fewer REDD allowances since it is cost-effective for China to abate more than other regions thereby allowing the Annex I countries to purchase more REDD credits. In 2040, these trading dynamics are more pronounced at the tails since abatement is more costly at the tails; therefore, the cost savings is initially observed at the tails of the distribution. These trading dynamics are also visible at the median as the differences in the amount of REDD credits purchased by the US in the *Annex I & China* scenario and the *Annex I* scenario are reduced (Figure 16). As in the deterministic results, in 2050, China significantly reduces REDD purchases thereby allowing Annex I countries to purchase more REDD; this allows the US to purchase more REDD credits and costs remain lower than the *Annex I* scenario.

Therefore, the effect of allowing China to purchase REDD offsets with Annex I regions introduces interesting dynamics. In the early years, the addition of China reduces cost savings from REDD due competition over demand. Starting in 2040, due stringent targets, China purchases fewer REDD offsets thus allowing Annex I nations to purchase more REDD; this results in cost savings at the tails of the distribution. Carbon prices continue to reduce in later years, such that expected costs in the *Annex I & China* scenario are lower than expected costs in the *Annex I* scenario.

		Carbon Price, $/tCO_2$			% Reduction from No REDD	
		No REDD	Annex I	Annex I & China	Annex I	Annex I & China
MEDIAN	2020	$31	$0	$0	100%	100%
	2025	$62	$1	$13	98%	79%
	2030	$83	$15	$30	82%	64%
	2035	$103	$39	$46	62%	55%
	2040	$133	$69	$69	48%	48%
	2045	$160	$92	$89	43%	45%
	2050	$217	$116	$113	47%	48%

Table 14. Median Carbon Prices and percent reduction from 'No REDD' Reference Case (with the addition of China)

		Carbon Price, $/tCO_2$			% Reduction from No REDD	
		No REDD	Annex I	Annex I & China	Annex I	Annex I & China
95th Percentile	2020	$45	$0	$2	100%	95%
	2025	$86	$12	$26	86%	70%
	2030	$115	$35	$50	70%	56%
	2035	$145	$71	$76	51%	48%
	2040	$181	$115	$112	37%	38%
	2045	$228	$145	$138	37%	40%
	2050	$344	$183	$169	47%	51%

Table 15. Carbon Prices at 95th percentile and percent reduction from 'No REDD' Reference Case (with the addition of China)

		Carbon Price, $/tCO$_2$			% Reduction from No REDD	
		No REDD	Annex I	Annex I & China	Annex I	Annex I & China
99th Percentile	2020	$54	$0	$4	100%	93%
	2025	$99	$17	$31	83%	68%
	2030	$132	$43	$62	68%	53%
	2035	$159	$90	$95	44%	40%
	2040	$201	$131	$123	35%	39%
	2045	$256	$177	$161	31%	37%
	2050	$433	$215	$197	50%	55%

Table 16. Carbon Prices at 99th percentile and percent reduction from 'No REDD' Reference Case (with the addition of China)

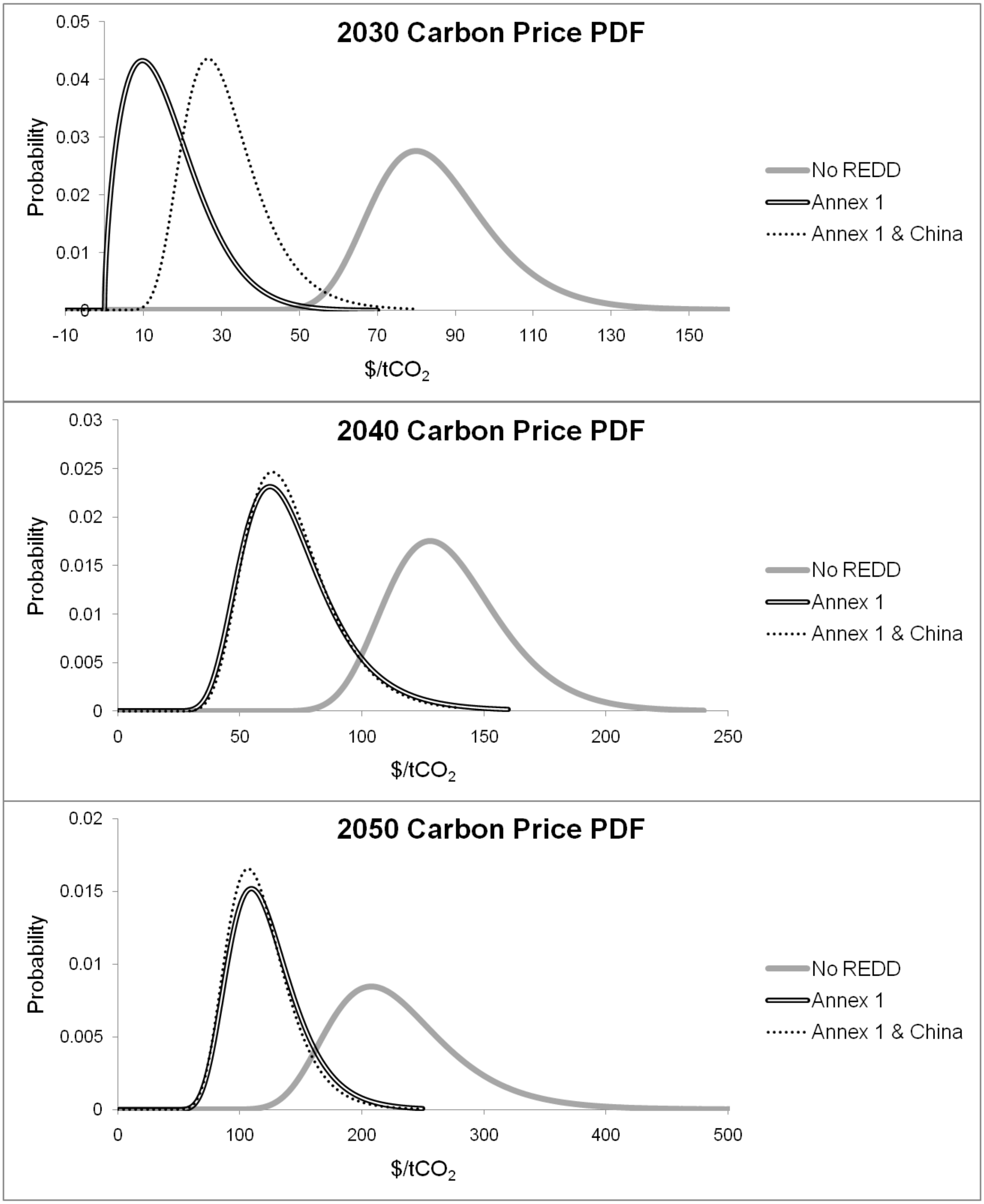

Figure 15. Carbon Price Distribution - China (2030, 2040, 2050)

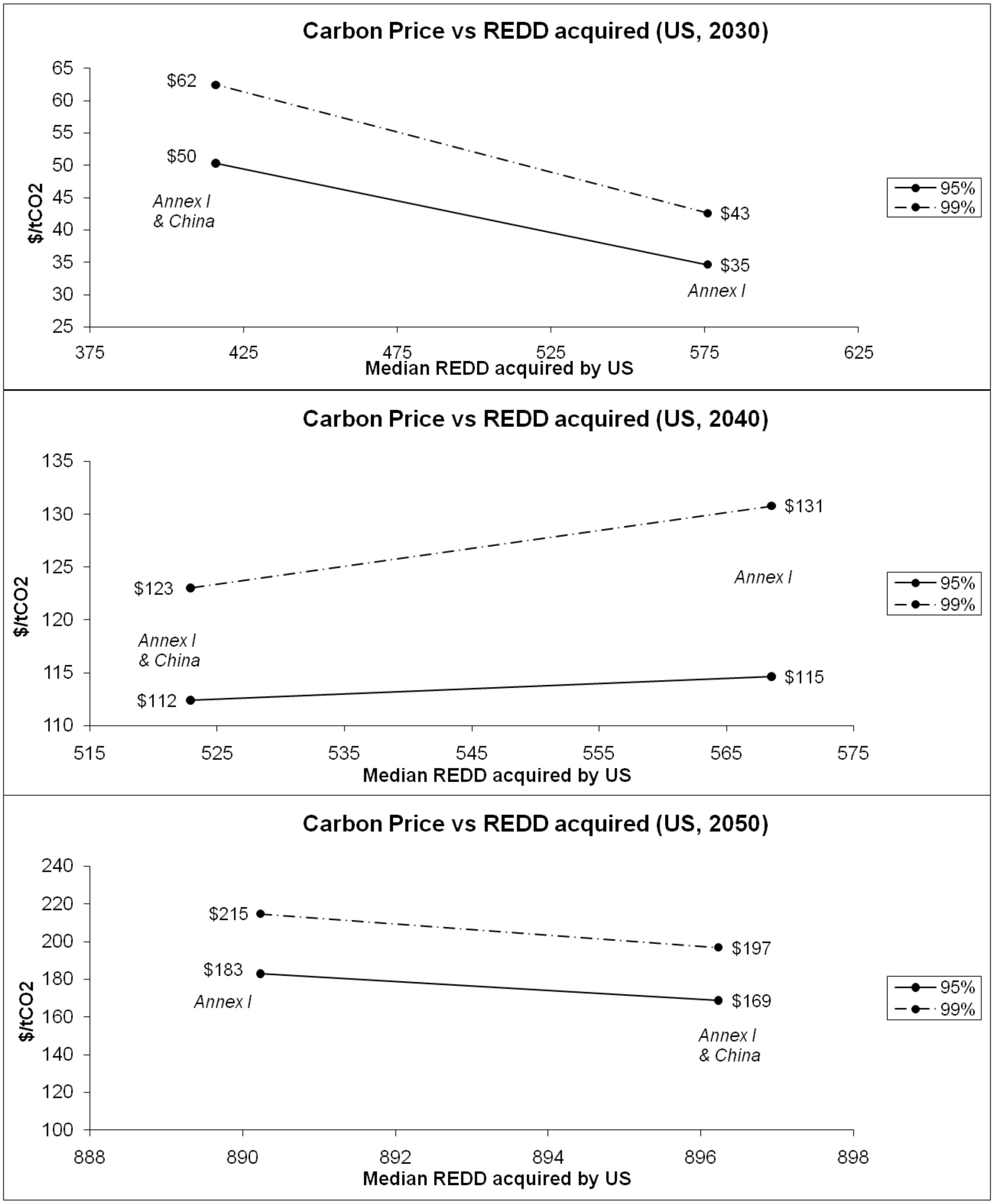

Figure 16. Carbon Price vs. Median REDD Acquired by US (China) in 2030, 2040, and 2050

6. Policy Implications

Based on the analysis presented above, carbon offsets such as REDD not only will lower expected costs, but also, have the potential to reduce upside carbon price uncertainties. Therefore, carbon offsets can provide an alternative cost-containment flexibility mechanism in climate change legislation. Carbon offsets are an attractive cost-containment instrument as it does not involve using domestic allowances, and it incentivizes further global participation to reduce global GHG emissions. In addition, growing demand for carbon offsets can increase development aid for carbon offset producing nations. The demand for carbon offsets as a cost-containment instrument would further incentivize the use of offsets in climate legislation, and rising demand of offsets from developed nations would encourage efforts to further expand the availability of more offsets, like REDD. In addition, the availability of REDD offsets in an emissions trading scheme would allow developed nations to utilize otherwise unavailable deforestation and forest degradation mitigation options thus providing the vital financial support to considerably curb deforestation. In addition, the increased interest in REDD could spur the development and standardization of monitoring and verification methods for REDD activities. Therefore, carbon offsets can offer benefits for both developed and developing nations, thereby promoting global participation.

Cost-containment instruments address a variety of cost uncertainties, such as start-up, short-term, and long term uncertainties (Webster et al., 2008a). The ability of carbon offsets to address these cost uncertainties depends on the supply of carbon offsets. Carbon offsets can address start-up cost uncertainties if there is a sufficient supply of offsets available during the inception of an emissions trading scheme. Short-term cost uncertainties can be addressed if carbon offsets are available for specific short periods of time, and long-term uncertainties can be addressed if carbon offset supply can be sustained for a long period of time.

Scarcity of offsets can reduce the cost-containment effectiveness, where scarcity can be affected by changes in the demand for and the supply of offsets. Current assessments of the supply of REDD offsets are based on assumptions of opportunity costs and deployment rates; therefore, uncertainties in opportunity costs and deployment rates can make assessing supply difficult. As shown in the results in Chapter 5, supply uncertainties due to uncertainties in opportunity costs and deployment rates can significantly affect the effectiveness of REDD as a cost-containment instrument. These uncertainties have the greatest impact in the early years thus affecting start-up cost containment effectiveness. In addition, if there is significant inter-year supply variability, this can limit short-term cost containment if carbon offset supply is too small to compensate for high carbon prices.

Moreover, increased offset scarcities in later years may be inevitable. As discussed in Section 4.2, emission targets tend get more stringent in later years. Emission target trajectories are typically constructed to be less stringent in earlier years to facilitate infrastructure changes, such as technology investment, to meet future emission targets. These increasingly stringent emission targets make offsets scarcer since stringent targets require purchasing larger amounts of offsets to compensate for the larger emission reductions thereby increasing the demand for offsets. Therefore, the effectiveness of offsets as a long-term cost-containment instrument will depend on whether the supply of offsets can increase in later years to meet the increased demand. However, opportunity costs for carbon offsets in later years are likely to increase as all low cost options are likely to be exhausted early. As offset opportunity costs rise and domestic mitigation efforts become cost competitive, the demand for carbon offsets will decrease as there are more cost-effective options. The combination of stringent targets and higher opportunity costs in later years reduces the likelihood for carbon offsets to address long-term price uncertainties effectively. Therefore, carbon offsets are likely to be more effective at containing start-up and short-term cost uncertainties, as long-term uncertainties are likely to persist due to stringent targets and higher opportunity costs.

Since carbon offsets reduce expected costs, it can delay domestic abatement efforts like clean energy and technology investments and can weaken consumer price signals to reduce energy consumption. These concerns are often translated into offset purchasing restrictions, such as the two billion metric ton CO_2 offset restriction in Waxman-Markey. These offset purchasing restrictions make offsets scarcer regionally; therefore, these restrictions can significantly reduce the cost-containment effectiveness of offsets as demonstrated in the results in Chapter 5. Alternatively, the Regional Greenhouse Gas Initiative (RGGI), a US Northeast and Mid-Atlantic State GHG reduction initiative, incorporates offsets as a sort of allowance reserve mechanism, where more offsets are allowed to enter the market when the trigger price is exceeded. RGGI initially limits offsets to 3.3% of a unit's total compliance obligation during a control period. If carbon prices exceed $7 (2005 dollars), allowed offsets increase to 5 percent, and if prices exceed $10 (2005 dollars), allowed offsets increase to 10 percent. This allows carbon offsets to primarily function as a cost-containment instrument for high carbon prices. The effectiveness of this mechanism is highly dependent on the allocated trigger price; low trigger price essentially allows carbon offsets to be available often, and an unrealistically high trigger price may never allow additional offsets to enter the market. These restrictions may deal with the concerns of low expected costs, but this can simultaneously reduce the supply of offsets, reducing participation from developing nations and possibly delaying necessary funding to developing countries. These purchasing restrictions significantly limit cost-containment for all three types of cost-uncertainties, since demand is limited for all years.

Start-up cost containment is heavily impacted by offset purchasing restrictions and supply uncertainties. If start-up cost uncertainties are particularly troublesome, supplementing offsets with another cost-containment instrument and/or delaying offset purchasing restrictions to later years may provide some relief.

Moreover, as more countries allow carbon offsets into their respective trading schemes, competition for carbon offsets can make offsets scarcer. The European Emissions Trading Scheme (EU ETS), which is the largest trading scheme in operation, has offset restrictions; these restrictions can have a significant effect on the supply of carbon offsets to other countries. EU ETS limits carbon offsets to non-forestry activities, and according to the draft amendment of the EU ETS Directive, it is likely to be excluded post-Kyoto (Streck et al., 2009). Under this scenario, a surplus of REDD allowances could exist for to non-European Union countries, which would provide substantial cost savings and reduced risk of upside carbon price uncertainties for non-European Union countries. However, competitiveness effects are significantly mitigated by supply uncertainties and domestic offset purchasing restrictions. Therefore, competition over offsets will likely play a minor role compared to regional offset purchasing restrictions and target stringency.

Linking emission trading schemes is an attractive option as it helps lower expected costs by taking advantage of lower abatement options among developed nations with emission commitments. However, flexibility mechanisms, such as cost-containment instruments, can complicate the linkage between trading schemes with divergent mechanisms. For example, linking a US emissions trading scheme that accepts forestry credits with EU ETS can weaken EU ETS restrictions on forestry credits; it would make forestry credits available in EU ETS thus weakening EU restrictions. One way to address these concerns is to filter out incompatible carbon offsets from the linked systems; this requires a comprehensive tracking system with strong enforcement mechanisms to ensure that these offsets do not enter non-compliant trading schemes, which will raise the transaction costs of the entire system.

For REDD, non-permanence further complicates linkage. Emission reductions from REDD may be subjected to non-permanence from events such as forest fires. As a result, someone needs to be responsible for maintaining permanence by restoring the released carbon. The designated party liable for non-permanence plays a significant role in linked schemes. If the producer of offsets is liable for non-permanence, linking is easy, provided that the trading systems to be linked have consistent accounting and verification rules. However, if buyers are liable for non-permanence, linking is complicated, especially when certain schemes do not allow REDD offsets, as in EU ETS (Streck et al., 2009). Trading schemes with REDD restrictions will be less inclined to link, but if they are linked, there must be provisions to track REDD credits to ensure they are not traded with EU ETS. Even if both linked schemes accept REDD offsets, the means of restoration needs to be subjected to verification, and each linked scheme should have standard rules and enforcement capacity to ensure that integrity is maintained. In both cases of linked systems, consistent standards are necessary as lax rules in one scheme can drive laxity throughout the entire linked system thus weakening all other schemes (Streck et al., 2009). In both cases, developed countries will need to work closely with offset producers to ensure and develop consistent standards, especially in the case when the producer is responsible for permanence.

Due to inherent supply uncertainties in carbon offsets, supplementing carbon offsets with other cost-containment instruments is recommended. In many cases, carbon offsets are not differentiated from domestic allowances and thus allowed to be banked as in the Waxman-Markey Bill. Similar to banking of allowances, banking offsets add intertemporal flexibility to the use of offsets; regions and sectors can defer the use of offsets for future years when targets are stricter and abatement costs are higher. Allowing the banking of offsets can be used to address longer term price uncertainties. However, banking offsets may increase the demand for offsets as participants in schemes that allow banking may result in purchasing additional offsets to bank thereby increasing offset scarcity for the years when banking is exercised. This increase in demand can disrupt supply for other regions. Therefore, during the years when banking is exercised, cost savings from REDD may be reduced as banking can make offsets globally scarce. In addition, since carbon offsets could delay domestic abatement efforts, banking carbon offsets may further delay abatement efforts as these banked offsets introduce additional low cost abatement options in future years, displacing and delaying the otherwise adopted domestic mitigation options. However, banking limitation provisions can be added to emissions trading schemes to restrict how long a permit can be banked. In Waxman-Markey, there are proposed expiration dates for offsets, which is a method to address these concerns. However, the effectiveness of banking as a supplemental instrument can be significantly limited by restrictions on offset purchases as these restrictions alone place significant limitations on cost-containment based on results in Chapter 5.

For REDD, non-permanence issues can also complicate banking. REDD offsets would need to be tracked and monitored to ensure that offsets are restored appropriately. In addition, if a REDD offset needs to be restored in a future year, the restored offset may need to be discounted depending on when the non-permanence occurs. The Waxman-Markey Bill allows borrowing allowances with interest (8 percent per year); this interest rate or similar can be applied to permanence activities. On the other hand, if the responsibility of permanence is on the producer of the REDD offset, then these permanence details need to be accounted for by the producer.

Carbon offsets are attractive for industrialized countries since they are generally cheaper than domestic abatement options. However, implementing carbon offsets requires additional administrative support that can add costs. For example, tracking and monitoring carbon offsets to ensure integrity within linked systems and within a scheme, especially in the case of banking and non-permanence, can add transaction and administrative costs. The extent of costs depends on who is liable for non-permanence and inconsistencies between linked systems that need to be addressed. However, liability for non-permanence may not make a difference, if producer liability costs are internalized in carbon offset opportunity costs.

This mechanism is just a temporary solution for price uncertainties, as these low cost carbon offsets will eventually be exhausted and price uncertainties are likely to persist. However, unlike more common cost-containment instruments, it does incentivize further involvement of developing countries, which is necessary for large GHG reductions in the future, by funding abatement projects via carbon offsets; these projects promote sustainable development hopefully paving the way for real GHG emission reduction commitments from developing countries in the near future.

In the end, increased use of carbon offsets to leverage cost-containment effects may be a mixed blessing for developing countries. Carbon offsets can provide the necessary support to move towards a more sustainable development path; however, when these developing countries move towards actual emission reduction commitments, these low cost abatement options will likely be exhausted. Therefore, there may be some equity concerns over abatement efforts as these developed nations enter into agreements, which may result in restricted output of carbon offsets to retain some of these options for the future. These supply restrictions will likely affect the cost-containment effectiveness of carbon offsets.

7. Conclusion

In this paper, I investigated whether carbon offsets can reduce carbon price uncertainties, specifically upside carbon prices. Because offset scarcity from changes in the demand for and supply of offsets can impact cost containment effectiveness; I examined the following supply and demand offset restriction scenarios on costs: (1) increasing competition over offset demand; (2) offset purchasing restrictions, and (3) supply uncertainties. Using REDD as a case study example, I analyzed these scenarios on REDD offsets in the EPPA model both deterministically and stochastically.

The results confirm that REDD lowers expected costs and more importantly reduces upside costs. Carbon prices at the 99th percentile were found to have at least a 51 percent reduction from the 'No REDD' reference case. Increasing competition over the demand reduces the cost savings from REDD, although the effect of competition is less pronounced in later years since emission targets are more stringent in later years. In addition, US offset purchasing restrictions substantially reduce cost containing effectiveness especially in the early years. Supply uncertainties also reduce effectiveness but less than the US offset purchasing restriction. Moreover, competition effects are muted in the presence of US offset purchasing restrictions and supply uncertainties as these restrictions impact offset scarcity more than from competition. Considering supply uncertainties and offset restrictions reduce effectiveness in the early years and the combination of stringent targets and increasing offset opportunity costs in later years, carbon offsets may be more effective at addressing short-term cost uncertainties.

Supplementing carbon offsets with another cost-containment instrument, such as banking, may help address scarcity concerns and help address longer term cost uncertainties. On the other hand, supplemental instruments may raise concerns about further delaying domestic action. In addition, offset purchasing restrictions can reduce the effectiveness of additional cost-containment instruments as offset scarcity can limit the amount of offsets that can be banked.

Carbon offsets can serve as an important cost-containment instrument that has the added benefit of encouraging participation by developing nations through the support of sustainable development activities in these developing nations. The demand for carbon offsets as a cost containment instrument would encourage efforts to further expand the availability of more offsets, like REDD, thereby further promoting the development and deployment of REDD offsets. The inclusion of REDD credits in emissions trading schemes could provide the necessary financial transfers to developing nations to substantially curb deforestation. However, offsets restrictions in current and proposed legislations can significantly reduce magnitude of these financial transfers.

Furthermore, incorporating carbon offsets to a trading scheme can add complications in linked systems. For example, forestry offsets are not permitted in the EU ETS; therefore, linked schemes need to be vigilant that these offsets do not leak into EU ETS thereby weakening EU restrictions. In addition, ensuring permanence for REDD offsets will require standard rules and verification methods to maintain integrity; these measures to ensure system integrity will add transaction and administrative costs. Moreover, equity concerns from developing nations, that low cost abatement options will be exhausted when they commit to actual emission reductions, may result in offset supply restrictions, which can also affect cost-containment.

7.1 Future Work

Banking is a good supplemental instrument to carbon offsets as it can add inter-year flexibility on the use of offsets; in fact, Waxman-Markey Bill allows the banking of offsets. In my model, carbon offsets were bought and consumed at the same time; there was no re-trading or banking. It would be interesting to simulate banking of offsets to understand the effects of banking on cost-effectiveness.

As mentioned in Chapter 7, RGGI uses offsets as an allowance reserve instrument, where if the trigger price is exceeded, more offsets are allowed to enter the system. It would be interesting to analyze carbon offsets as an allowance reserve, with a sensitivity analysis on different allowance reserve restrictions, such as trigger prices and offset quantities allowed. This can be compared to the results from the US Waxman-Markey 1bmt international offset restriction.

For my initial REDD supply, I assumed that the maximum available REDD was where the costs went vertical. It would be more realistic to insert the REDD MAC curves in EPPA, such that REDD supply was determined by equating marginal costs between EPPA's MAC and REDD MAC. This may involve linking forestry models, like GTM, with a forward-looking EPPA model. The two models may need to run concurrently as the GTM model will need account for the forestry abatement options exercised in the EPPA model, and the EPPA model will need abatement costs from the GTM model to determine the share of abatement activity from the forestry sector. Alternatively, forestry assumptions can be added into the EPPA model to account for available forestry abatement opportunities.

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Appendix

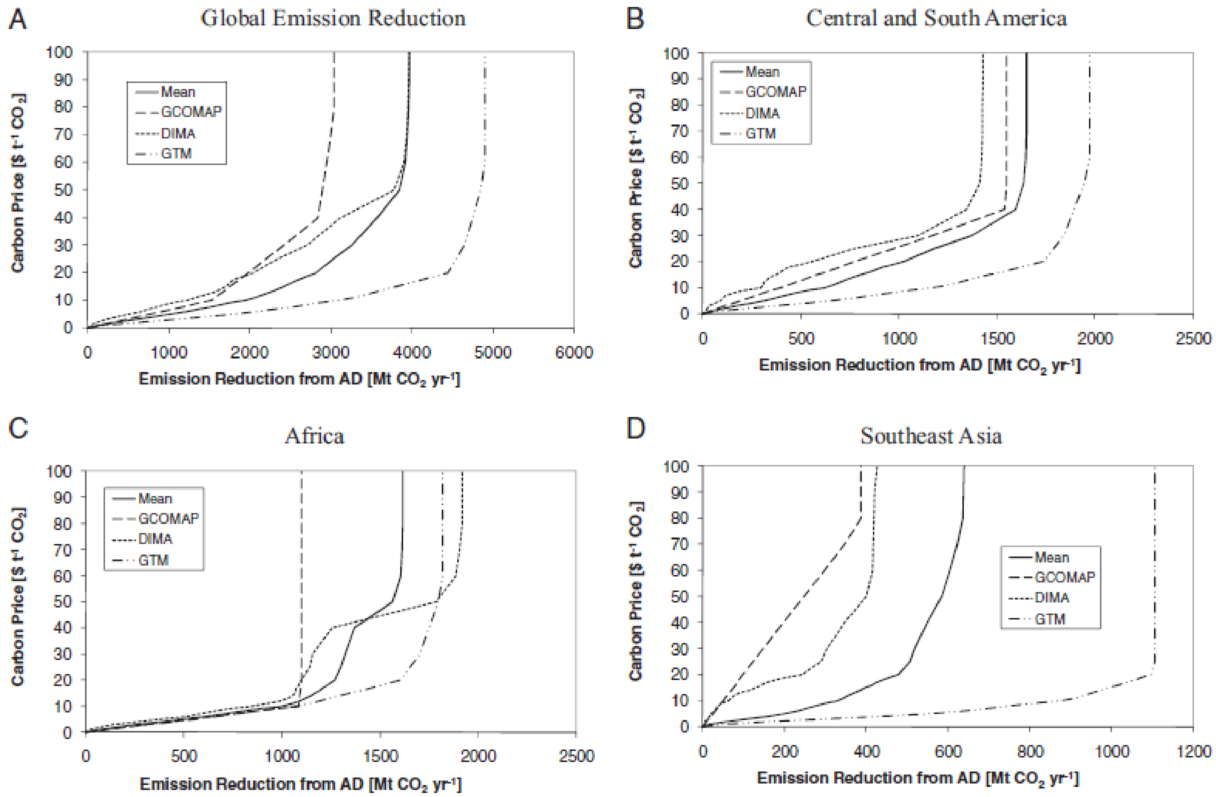

Figure A1. Marginal Costs of emission reductions from avoided deforestation activities in 2010 in three regions from three models (Kindermann et al., 2008)

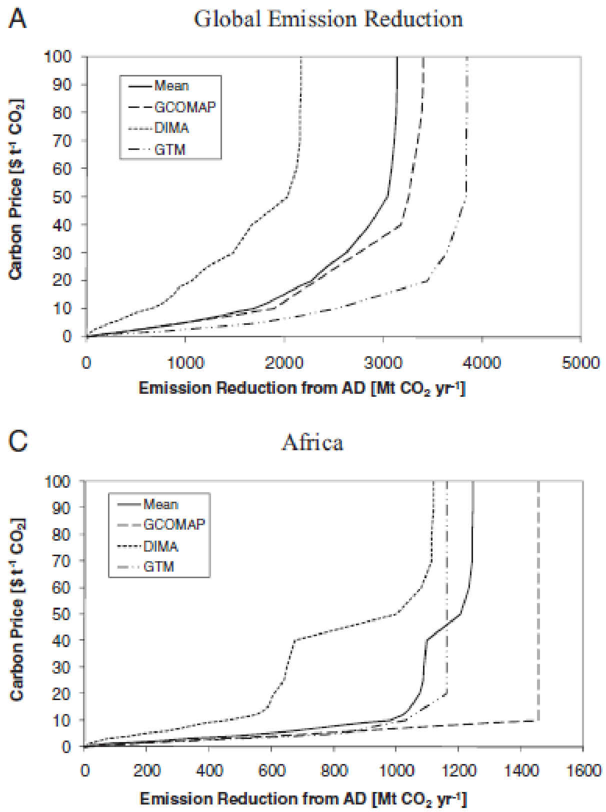

Figure A2. Marginal Costs of emission reductions from avoided deforestation activities in 2030 in three regions from three models (Kindermann et al., 2008)

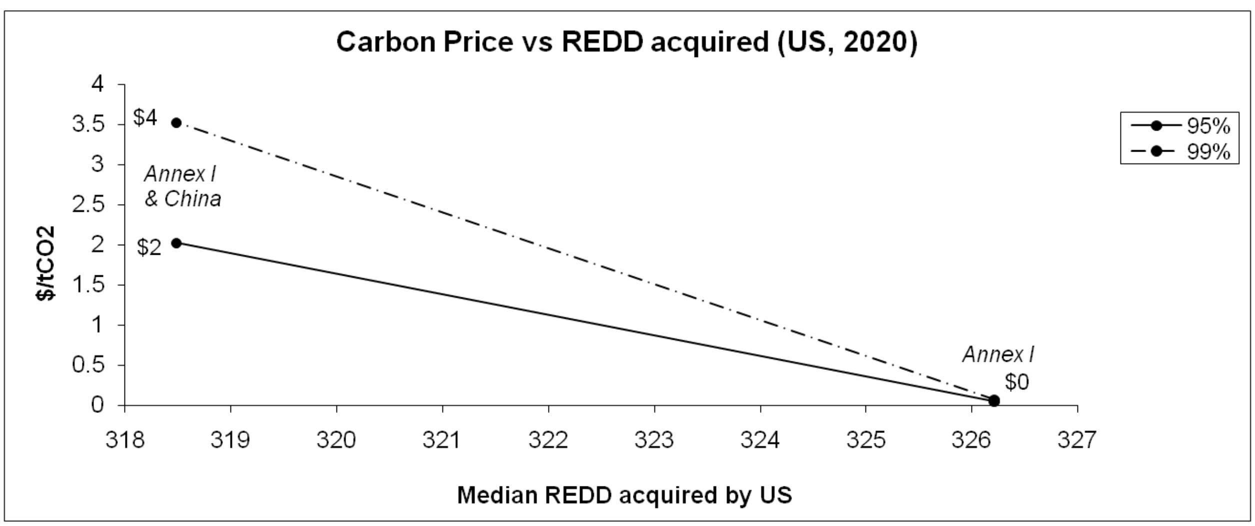

Figure A3. Carbon Price vs. Median REDD Acquired by US (China) in 2020

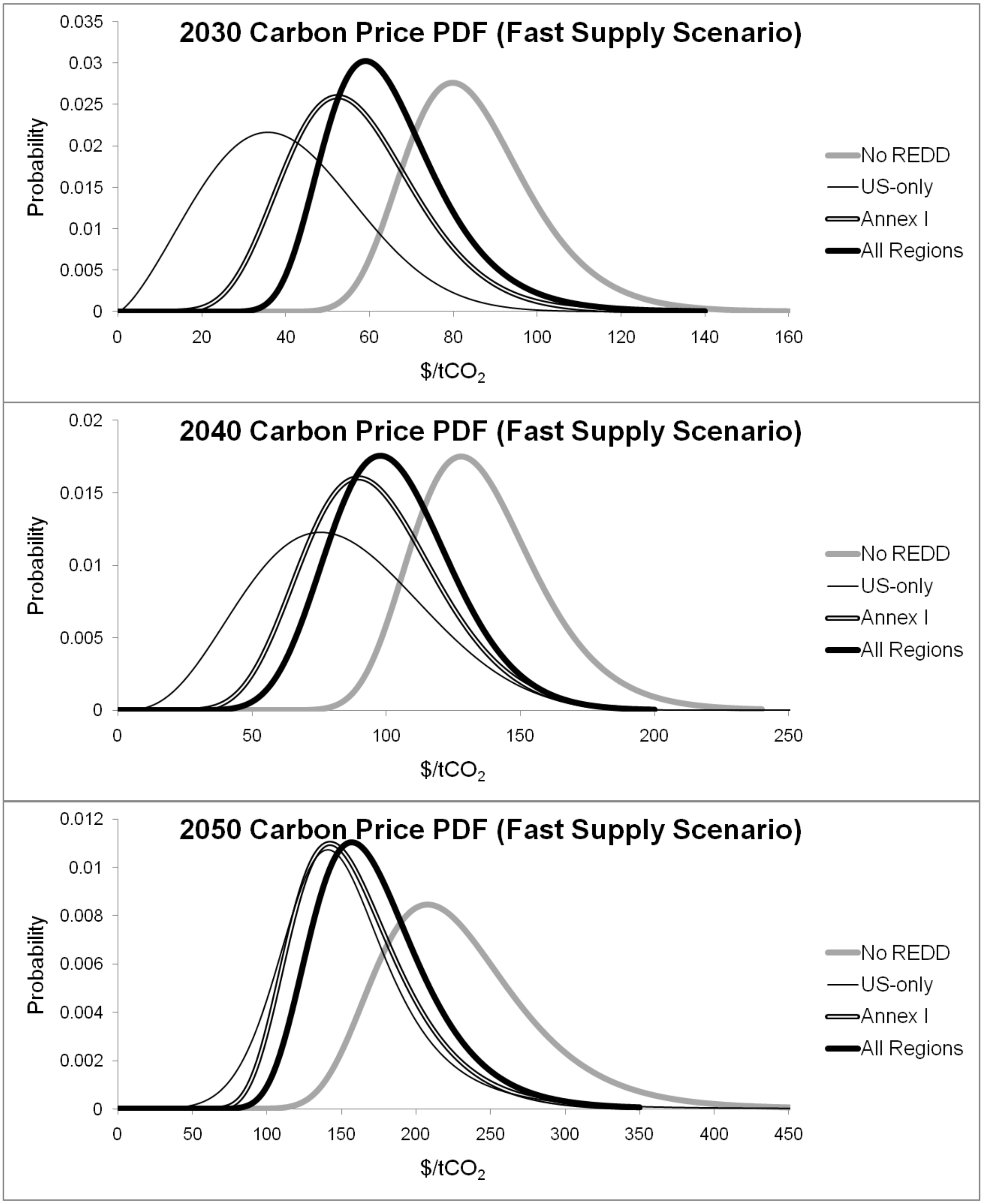

Figure A4. Carbon Price vs. Median REDD Acquired by US for Fast Supply Scenarios (2030, 2040, 2050)

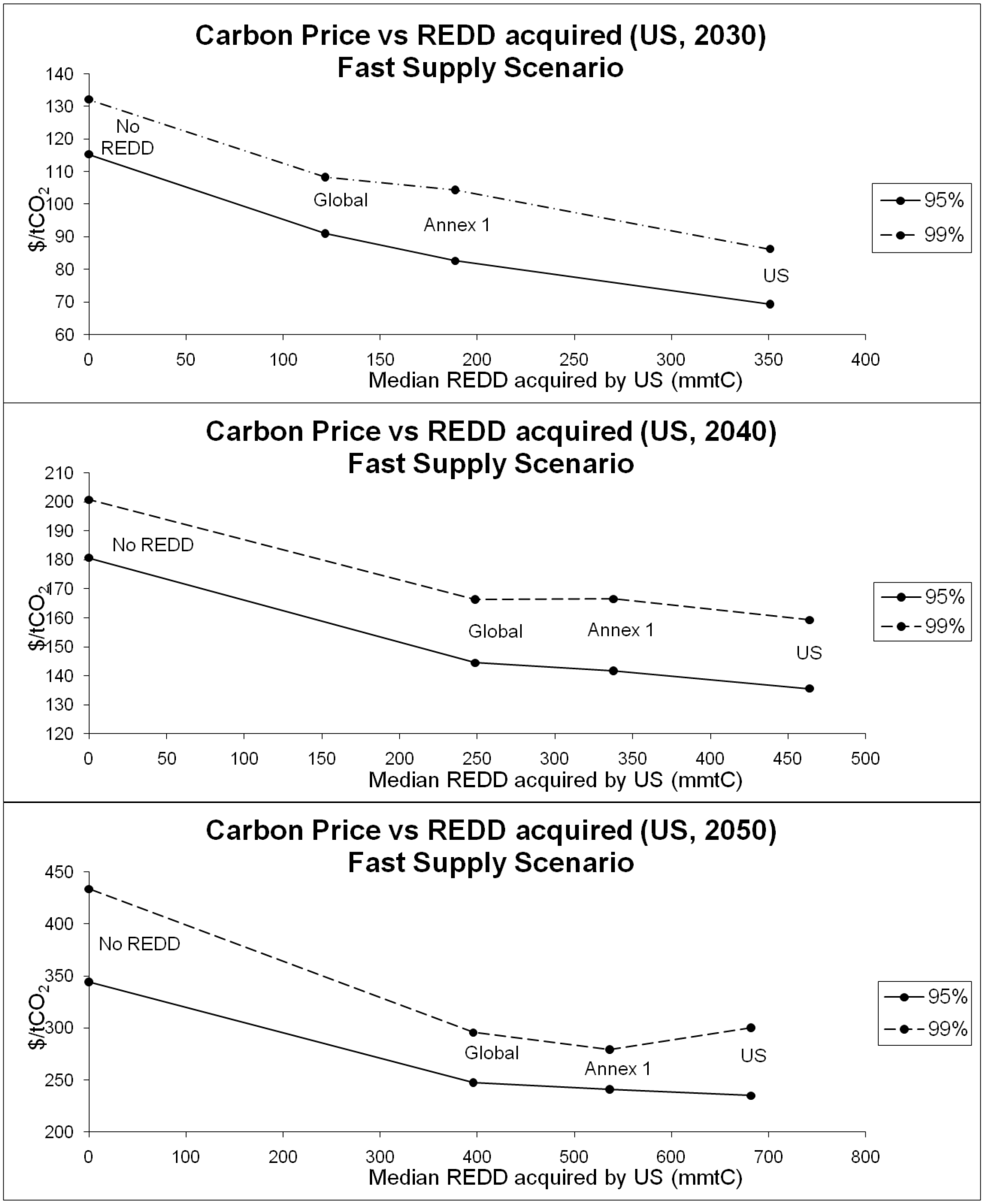

Figure A5. Carbon Price vs. Median REDD Acquired by US for Fast Supply Scenarios (2030, 2040, 2050)

		Carbon Price, $/tCO$_2$				% Reduction from No REDD		
		No REDD	US-only	Annex I	All Regions	US-only	Annex I	All Regions
MEDIAN	2020	$31	$11	$18	$23	63%	40%	25%
	2025	$62	$29	$42	$48	53%	32%	23%
	2030	$83	$39	$56	$63	54%	33%	24%
	2035	$103	$53	$71	$76	49%	31%	26%
	2040	$133	$82	$94	$102	39%	29%	24%
	2045	$160	$112	$116	$123	30%	28%	23%
	2050	$217	$149	$156	$169	31%	28%	22%

Figure A6. Median Carbon Prices for different trading scenarios and percent reduction from 'No REDD' Reference Case (Fast Supply Uncertainty Scenario)

		Carbon Price, $/tCO$_2$				% Reduction from No REDD		
		No REDD	US-only	Annex I	All Regions	US-only	Annex I	All Regions
95th Percentile	2020	$45	$23	$31	$34	50%	32%	24%
	2025	$86	$51	$61	$69	41%	29%	19%
	2030	$115	$69	$83	$91	40%	28%	21%
	2035	$145	$94	$109	$113	35%	25%	22%
	2040	$181	$136	$142	$144	25%	22%	20%
	2045	$228	$178	$170	$176	22%	25%	23%
	2050	$344	$235	$241	$247	32%	30%	28%

Figure A7. Carbon Prices at 95th percentile for different trading scenarios and percent reduction from 'No REDD' Reference Case (Fast Supply Uncertainty Scenario)

		Carbon Price, $/tCO$_2$				% Reduction from No REDD		
		No REDD	US-only	Annex I	All Regions	US-only	Annex I	All Regions
99th Percentile	2020	$54	$30	$36	$41	44%	33%	23%
	2025	$99	$64	$75	$83	35%	25%	17%
	2030	$132	$86	$104	$108	35%	21%	18%
	2035	$159	$113	$132	$134	29%	17%	16%
	2040	$201	$159	$167	$166	21%	17%	17%
	2045	$256	$230	$207	$208	10%	19%	19%
	2050	$433	$300	$279	$296	31%	36%	32%

Figure A8. Carbon Prices at 99th percentile for different trading scenarios and percent reduction from 'No REDD' Reference Case (Fast Supply Uncertainty Scenario)