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Linking Reduced Deforestation and a Global Carbon Market: Impacts on Costs, Financial Flows, and Technological Innovation

Valentina Bosetti,[1] Ruben Lubowski,[2] Alexander Golub,[2] and Anil Markandya[3]

Discussions over tropical deforestation are currently at the forefront of climate change policy negotiations at national, regional, and international levels. This paper analyzes the effects of linking Reduced Emissions from Deforestation and Forest Degradation (REDD) to a global market for greenhouse gas emission reductions. We supplement a global climate-energy-economy model with alternative cost estimates for reducing deforestation emissions in order to examine a global program for stabilizing greenhouse gas concentrations at 550 ppmv of CO_2 equivalent. Introducing REDD reduces global forestry emissions through 2050 by 20-22% in the Brazil-only case and by 64-88% in the global REDD scenarios. At the same time, REDD lowers the total costs of the climate policy by an estimated 10-25% depending on which tropical countries participate and whether the "banking" of excess credits for use in future periods is allowed. As a result, REDD could enable additional reductions of at least 20 ppmv of CO_2-equivalent concentrations with no added costs compared to an energy-sector only policy. The cost savings from REDD are magnified if banking is allowed and there is a need to increase the stringency of global climate policy in the future in response, for example, to new scientific information. Results also indicate that REDD decreases carbon prices in 2050 by 8-23% with banking and 11-26% without banking. While developing regions, particularly Latin America, gain the value of REDD opportunities, the decrease in the carbon price keeps the value of international carbon market flows relatively stable despite an increase in volumes transacted. We also estimate that REDD generally reduces the total portfolio of investments and research and development of new energy technologies by 1-10%. However, due to impacts on the relative prices of different fossil fuels, REDD has a slight positive estimated effect on investments in coal-related technologies (IGCC and CCS) as well as, in some cases, non-electric energy R&D. This research confirms that integrating REDD into global carbon markets can provide powerful incentives for the preservation of tropical forests while lowering the costs of global climate change protection and providing valuable policy flexibility.

Keywords: Climate change, deforestation, carbon sinks

JEL Classification: Q23, Q34, Q54

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1. Introduction

As scientific evidence grows that atmospheric concentrations of greenhouse gases (GHGs) are already near or above levels that pose dangerous risks of warming over the long term, policymakers are increasingly focusing on strategies to quickly reduce emissions across as many sectors as possible. In particular, policies for Reducing Emissions from Deforestation and Forest Degradation (REDD) offer an immediate opportunity to mitigate a major share of global greenhouse gas emissions at relatively low estimated costs (Stern 2008).[4] International forest carbon efforts could also offer an attractive "wooden bridge" for reducing near-term emissions while buying time to adapt to a low carbon future (Chomitz 2006). In the absence of certainty over long-term emissions targets, early emissions reductions also have particular value as a global insurance policy that keeps options open to avoid potentially much greater economic costs and climate risks in the future (Fisher et al. 2007).

While the framework for limiting greenhouse gases under the Kyoto Protocol excluded the tropical forest sector, debates over approaches for REDD have risen to the forefront of current negotiations on a new climate change regime under the United Nations Framework Convention on Climate Change (UNFCCC). International forest carbon has also been central to deliberations over the next phase (2013-2020) of the European Union's Emissions Trading Scheme (ETS) as well as recent proposals for climate change policies in the United States.

This paper investigates the implications of linking REDD credits to a global market for GHG emission reductions. We use a global climate-energy-economy model to conduct the first integrated analysis of how including deforestation in a global trading system for emission reductions would affect deforestation emissions, climate policy costs, emissions permit prices, technology innovation in the energy sector, and the pattern of mitigation efforts and financial flows across countries and over time.

At the international level, a focal point of discussions over REDD is the extent to which forest carbon should be financed through a market-based trading system for forest carbon credits or through a separate "fund" drawn from dedicated tax revenues, proceeds from GHG emission allowance auctions, or voluntary government contributions (e.g., Karousakis and Corfee-Morlot 2008; UNFCC 2007). Governments and other organizations have put forth multiple proposals for raising funds as well as alternative market-based approaches with varying degrees of "fungibility" between forest carbon credits and GHG reductions in other countries and sectors.[5] Policymakers in the United States are also considering including international forest carbon to varying degrees within emerging regional GHG reduction markets as well as in the most recent legislative proposals for a cap-and-trade system at the Federal level.[6]

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[4] The latest IPCC report estimates that destruction of tropical forests and peat lands contributed 17.5% of global anthropogenic GHG emissions in 2004 – greater than the entire global transport sector, and about the same scale as all fossil fuel emissions from China or the United States (Rogner et al. 2007). More recent data put this share at 12% and, likely, higher depending on the share of peat fires on unmanaged lands attributed to human activities (WRI CAIT, forthcoming; Houghton 2008).

[5] Parker et al. (2008) provide a user-friendly guide to the most recent and influential proposals for REDD, including the alternative financing options. See http://www.globalcanopy.org/themedia/file/PDFs/TheLittleREDDBook_Nov2008.pdf

[6] For example, the Boxer-Lieberman-Warner proposed and debated in the Senate in Summer 2008 allowed the use of forest carbon credits up to 10% of total annual emissions. The Waxman-Markey draft bill released from the House of Representatives on March 31, 2009, sets an absolute limit of 1 billion tons per year on the allowed use reduced deforestation and other international mitigation credits from uncapped nations, although these "offsets"

Under a carbon market system, mitigation of tropical forest emissions, perhaps measured at a national scale against a reference level of historic emissions, would generate credits that could be sold and traded in a market for GHG emissions permits or "allowances" that could be used to satisfy legally-binding emissions control obligations. A concern is that widespread availability of low-cost international forest carbon credits could "flood" this carbon market, making the price "too cheap" and diverting investment from efforts to develop low-carbon technologies. We would argue that this is largely misplaced: reducing the costs of climate change protection by steering efforts into the lowest marginal cost options for mitigation is precisely the economic rationale for an emissions trading system, providing a net gain for society as whole as long as the right long-term incentives are in the place and the desired atmospheric benefits are achieved. Concerns over "flooding" have been largely voiced with regards to the scale of potential forest carbon credits relative to the size of the European Union's existing ETS market. For example, the European Commission cited a potential imbalance between the supply and demand for REDD credits as one of the reasons for its recommendation to exclude REDD from the EU ETS at the end of last year (EC 2008). Of course, if there is a concern that forest carbon credits will be too plentiful, policy makers always have the option of limiting the numbers allowed in the system and it is surprising that this has not been taken up by the EU in its revised ETS proposals. At the same time we should not lose sight of the costs of excluding REDD from the carbon market: doing so risks making the costs of climate change protection unnecessarily expensive and misses important opportunities to enable political agreement on more stringent GHG reduction targets.

1.1. Previous studies of the impacts of global forests on climate stabilization and carbon markets

Previous analyses of reduced deforestation and other land-based mitigation activities using integrated economy-climate models have focused on the potential contribution to a least-cost portfolio of mitigation options for achieving a particular target level of GHG concentrations. Results from the Energy Modeling Forum 21 at Stanford University and related efforts suggest that reducing deforestation, in addition to afforestation/reforestation, changes in forest management, and other land-based options to mitigate GHG emissions from agriculture, can provide important cost-savings for reaching climate stabilization goals over the next century (Rose et al. 2007; Fischer et al. 2007). These cost savings may enable greater global emissions reductions than could be achieved without REDD for the same overall cost.

For example, according to Tavoni, Sohngen, and Bosetti (2007), including emissions reductions from deforestation, afforestation and reforestation (A/R) and changes in forest management enables an atmospheric target of 550 CO_2 parts per million by volume (ppmv) for the same total cost as a 600 ppmv target without forestry mitigation. The estimated net cost savings of US$2 trillion (40% of policy costs in discounted terms) could finance an estimated additional 0.25°C less warming by the end of the century at no added cost compared with energy-sector only reductions. They also find that in meeting the emissions reductions target, forestry crowds out some of the abatement in the energy sector for the first 2–3 decades

would be subject to a 20% discount. The bill also includes a "strategic allowance reserve" that allows additional use of deforestation reduction credits if the carbon price hits particular levels. All the recently proposed bills also dedicate a portion of allowance auction revenues to fund additional international forest carbon activities.

and energy-intensity R&D investments are decreased by 10%.[7] Researchers have also estimated that forest-sector activities, largely in the tropics, would contribute half as much abatement as the total energy sector under an economically optimal strategy that balances mitigation costs versus the economic benefits of avoiding climate change (Sohngen and Mendelsohn 2003).

Most economic assessments of the contribution of the forest sector to global climate stabilization policies have abstracted from the institutional details of how national commitments would be structured and how emission reductions would be traded in a carbon market system. Our analysis builds upon Tavoni, Sohngen, and Bosetti (2007), who first used the World Induced Technical Change Hybrid (WITCH) model to study the effect of including forest carbon mitigation on a climate stabilization policy. The large potential for REDD found in their analysis builds partly on the moderate target they consider (550 ppmv CO_2 only[8]) and partly on the assumption of full availability of mitigation opportunities from avoided deforestation as well as afforestation, reforestation and changes in forest plantation management worldwide. Their analysis provides a benchmark portraying the full potential contribution of forests to climate change mitigation. Our analysis focuses on a more stringent target and includes forestry mitigation through avoided deforestation only. Their focus was also on the economically efficient pattern of mitigation, without considering a potential market for trading emission reductions based on negotiated national-level commitments. In contrast, we examine the trade of emission reductions, both across countries and over time, and model a policy scenario to reflect the expected outcome of negotiations in which only industrialized countries agree to particular targets for emission reductions initially, with developing nations accepting emission-reduction commitments at a later stage. In addition, our analysis incorporates potential restrictions on trading between industrialized and developing nations during the early years of the market.

More recently, a small set of studies has examined the impacts of including forest carbon credits within a global carbon market. While these analyses have all found significant cost savings from introducing forest-based mitigation, specific results vary with fundamental assumptions regarding the supply and demand for forest carbon credits and the particular design of the trading system. The estimated impacts on prices depend on the modeled demand for forest carbon credits, based on the emission reductions targets in each period, the imposed restrictions on carbon market trading, and the available alternatives for mitigation in other sectors. Anger and Sathaye (2006) and a recent update by Dixon et al. (2008) find a 30% cost saving from introducing REDD into a single-period market that ends in 2020, based on announced targets from Annex 1 nations. They estimated the carbon price is reduced by 45% in the case of unlimited REDD trading and by 20% when tropical forest credits are restricted to 20% of Annex 1 mitigation. The modeled scenario also allows unlimited credits for developing country mitigation from projects under the Clean Development Mechanism of the Kyoto Protocol, which reduces the carbon price by almost 60% compared to a market without CDM trading (Dixon et al. 2008).

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[7] As in the present analysis, "energy-intensity R&D" refers to research and development investments to foster improvements in energy efficiency in both the electric and non electric sectors.

[8] A stabilization level of 550 ppmv CO_2 only (corresponding to about 650 ppmv CO_2 equivalent, depending on assumptions regarding non-CO_2 gases) would result in minimal chances of meeting the frequently discussed 2.0°Celsius limit on average global temperature rise above preindustrial levels. The stabilization target considered in the present paper is 550 ppmv CO_2 eq (roughly 450 ppmv CO_2 only). Again, at these concentration levels, depending on the sensitivity of the climate system, the likelihood of meeting the 2.0° C target is low. While current attention is thus focused on even more stringent goals, we choose this more moderate target because it has received wide attention in the policy arena and provides greater scope for analyzing the technology implications of linking REDD to a carbon market system, as discussed in section 3.

The Eliasch (2008) study for the U.K. Office of Climate Change also explores the effect of "supplementarity" limits on the share of emission-reduction requirements that can be satisfied through international credits, but apply these to both tropical forest carbon and CDM. They find that adding REDD as well as afforestation/reforestation credits from developing countries would lower the European Union's carbon price in 2020 by 4% to 41%, depending on whether the EU commits to 20% or 30% reductions below 1990 levels by 2020. These estimates are reduced greatly depending on the assumed "supplementarity" limits on the share of emission-reduction requirements that can be satisfied through REDD and other international credits. The study reports that the costs of reducing global emissions to 50% of 1990 levels by 2050 (475 CO_2 equivalent stabilization) may be lowered by 25–50% in 2030 and 20–40% in 2050 when reduced deforestation and afforestation/reforestation options are included. The analysis suggests that cost savings of almost US$2 trillion could finance a 10% lower global emissions target in 2050. A cumulative reduction of 10% in global GHG emission through the century has the potential to reduce global mean temperatures by roughly 0.2-0.25° Celsius by the end of the century.

These prior studies were static analyses that considered targets for each period in isolation, without examining the potential dynamic incentives created by credible long-term targets. When the long-term targets are sufficiently ambitious and anticipated, regulated entities have a potential incentive to over-comply with respect to their current requirements and "bank" excess allowances or other types of credits for use in later periods when allowance prices could be higher, as is likely the case with tightening commitments to reduce emissions (Dinan and Orszag, 2008; Murray, Newell and Pizer, 2009). This flexibility over the timing of abatement efforts potentially creates an added source of demand for abatement from all sectors, including forestry, in the present, driven by the anticipated needs to undertake more expensive emissions cuts in the future.

Taking banking into account and assuming a fixed emissions reductions path consistent with a stabilization target of about 550 CO_2 equivalent, Piris-Cabezas and Keohane (2008) estimate that a program to reduce tropical deforestation emissions would lower the global carbon price by 13%, while also including afforestation/reforestation and changes in the management of timber plantations would reduce the price by 31%, over 2012 to 2050. With double the estimated supply of REDD credits, the price declines by about 23%, as additional credits are "banked" and used gradually over time. This also suggests that the reservoir of banked credits could provide firms with a buffer against unexpected price spikes and volatility in the future (Piris-Cabezas and Keohane 2008).

In addition to banking, financial options based on low cost sources of abatement available today, such as REDD, could provide an alternative form of flexibility to help hedge against carbon market volatility (Golub and Greenberg 2009). Rather than examining the role of REDD credits that can be directly used for compliance with emissions reduction obligations, recent research has examined the potential role of options to purchase REDD credits at a future date, depending on the carbon prices prevailing at that time. Such options could provide an alternative source of financing for deforestation reductions while hedging firm-level risks associated with development of new energy technologies such as carbon capture and storage (Golub et al. 2008).

1.2 Key features of the analysis

Compared with previous analyses of the impacts of including tropical REDD and other forest sector activities in a global carbon market, our study is distinguished by three principal features.

First, we use an integrated assessment model, which links the economy and the climate, to analyze the impacts of linking REDD to a global carbon market. Rather than only examining the market impacts, the link to the climate allows consideration of how the predicted patterns of mitigation affect GHG concentrations and the associated climatic implications. This enables explicit analysis of the costs of meeting stabilization targets, as well as the degree to which cost savings from forest carbon mitigation can enable more ambitious stabilization objectives. The climate module also allows us to examine alternative estimates for the costs of reducing emissions from deforestation while accounting for differences in the projected business-as-usual levels of future emissions from global forests. Accounting for varying trajectories of forest emissions is essential for evaluating the role of global forests in meeting stabilization targets. We also use the integrated assessment framework to examine the role of reductions in deforestation under different scenarios on how stabilization policies might evolve over time in response, for example, to new scientific information about the sensitivity of the climate system. This allows us to explore the potential value of tropical forest carbon as a global "hedging strategy" that could keep open options to avoid higher costs and climate risks in the future.

Second, technological change is treated endogenously through our use of the WITCH model. We build on the analysis of Tavoni, Sohngen, and Bosetti (2007) to directly model how REDD alters incentives through the carbon market and how these, in turn, affect the pattern of technology innovation and deployment in the energy sector over time. Previous studies of the impacts of tropical forest mitigation on carbon prices take future technologies and abatement costs as fixed. Consideration of induced technical change is critical for climate policy evaluation in general and, specifically, for assessing the consequences of linking REDD to a global carbon market and the potential for "market flooding." The consequences for energy technologies are also important for assessing the value of forestry mitigation as a "bridge" to facilitate the transition to a future low-carbon economy.

Third, our study is intertemporal and dynamic. We incorporate how future climate policy targets that are credible and anticipated determine the expectations of market participants, influencing mitigation actions and investment decisions in the present. Re-engineering the world economy to mitigate climate change is a long-term proposition, and modeling future expectations is critical for understanding decisions to invest in new technologies that will only gradually bear fruit over time. The dynamic model also allows us to explore the impact of a market framework in which participants can "bank" credits for emissions reductions so as to meet more ambitious emissions cuts in the future. This likely feature of carbon markets has significant implications for the timing and pattern of abatement across forestry and other sectors.

1.3 Overview of the paper

The remainder of the paper is divided into four sections. Section 2 describes the WITCH model and the alternative sources of supplemental data on the marginal costs of reducing tropical deforestation. Section 3 presents our policy scenarios, based on a global program for stabilizing greenhouse gas concentrations at 550 ppmv of CO_2 equivalent. We also explore the implications of alternative estimates of REDD supply, the availability of banking, and the need to make midcourse corrections in the climate stabilization policy. In section 4, we report and discuss the results, focusing on the impacts on deforestation, policy costs, carbon prices, technological change, and financial flows among countries. Section 5 concludes and identifies areas for future research.

2. The WITCH Model and the Forestry Data

The analysis is performed by supplementing an optimal growth integrated assessment model (WITCH) with cost curves for reducing tropical deforestation derived from different forestry models. The WITCH model (Bosetti, Carraro *et al*., 2006) is a climate-energy-economy model designed to assist in the study of the socio-economic dimension of climate change. It is structured to provide information on the optimal responses of world economies to climate damages and to identify impacts of climate policy on global and regional economic systems.[9]

WITCH is a hybrid model because it combines features of both top-down and bottom-up modeling: the top-down component consists of an inter-temporal optimal growth model in which the energy input of the aggregate production function has been expanded to yield a bottom-up description of the energy sector. The model provides a fully intertemporal allocation of investments in energy technologies and research and development (R&D) that is used to evaluate optimal and second-best economic and technological responses to different policy measures.

Countries are grouped in 12 regions that cover the world and whose strategic interactions are modeled through a dynamic game. The game theory set-up accounts for interdependencies and spillovers across regions of the world, and equilibrium strategies reflect inefficiencies induced by global strategic interactions. This allows the analysis of fully cooperative equilibria (for example, in the case in which all regions of the world sign a climate agreement) and partial/regional coalitional equilibria (when only a subgroup of regions signs a climate agreement or different groups of regions sign different agreements).

In WITCH, technological progress in the energy sector is endogenous, thus enabling us to account for the effects of different stabilization policies on induced technical change, via both innovation and diffusion processes. The role of endogenous technical change has been shown to be critical for modeling climate policies. A recent OECD working paper provides a more exhaustive analysis of this issue featuring the WITCH model (Bosetti et al. 2009). The model's dynamic system also accounts for feedback effects from economic variables to climatic variables, and vice versa.[10]

Several features of the model allow us to investigate a number of issues in greater detail than most of the studies in the existing literature. First, though quite rich in its energy modeling and close in spirit to bottom up energy models, WITCH is based on a top-down framework that guarantees the coherent, fully intertemporal allocation of investments. Second, the model can track all actions that have an impact on the level of mitigation – R&D expenditures, investment in carbon free technologies, purchases of emission permits or expenditures for carbon taxes as well as biological sequestration credits – and can thus evaluate equilibrium responses stimulated by the introduction of REDD. This leads to a transparent evaluation of abatement costs and to a clearer quantification of the uncertainties affecting them.

Diffusion and innovation processes are modeled to capture advancements in carbon mitigation technologies, through both learning by doing and research. The model also explicitly includes the effects

[9] A throughout description and a list of papers and applications are available at www.feem-web.it/witch.

[10] The model is solved numerically in GAMS/CONOPT for 30 5-year periods, although only 20 are retained as we do not impose terminal conditions. Solution time for the baseline scenario is approximately 30 minutes on a standard Pentium PC.

of international technology spillovers and captures innovation market failures. The detailed representation of endogenous technical change and the explicit inclusion of spillovers in technologies and knowledge are crucial to understanding and assessing the impact of REDD on innovation.

Given uncertainty surrounding both tropical forestry emission baselines and the costs of reducing deforestation for different regions and time periods, we run three experiments each based on a different set of REDD cost curves derived from a distinct modeling framework external to the WITCH model. We focus on avoided deforestation for which a broad range of cost estimates is available, as this is the focus of REDD policy discussions. One set of supply curves comprise the estimated compensation needed to cover 30 years of costs of reducing deforestation emissions in the Brazilian Amazon based on a spatially-explicit, bottom-up model from the Woods Hole Research Center (Nepstad et al. 2007). While only one out of many potential participating countries in a global REDD program, Brazil accounts for up to one half of global deforestation in the humid tropics (Hansen et al. 2008), and has the most developed current infrastructure for monitoring and implementing REDD. In August, 2008, the government of Brazil established a fund to protect the Amazon forest with the goal of raising $21 billion in international contributions over the next 13 years. At the UN climate conference in Poznan, Poland, in December 2008, Brazil further announced a voluntary commitment to reducing its deforestation by 70% over 2006 to 2017 relative to the average deforestation levels over the previous decade (Government of Brazil 2008). Though Brazil is seeking international contributions for the purposes of achieving this target, it has officially indicated aversion to trading forest carbon in a GHG allowance market. Nevertheless, given Brazil's institutional capabilities and expressed commitment to reducing deforestation, Brazil-only REDD is potentially a realistic scenario for near-term REDD potential.

We also use two other sets of estimates of the global potential for reducing deforestation emissions, assuming that all tropical forest nations could immediately join a carbon trading system and had the institutional and governance capacity to implement deforestation-reduction programs. While countries vary widely in their willingness and ability to implement REDD at the present time, the global results indicate the maximum economic potential that could be tapped under an optimal REDD system. These data are based on two of the leading economic models of global forests, based on scenarios for rising carbon prices consistent with those in our policy simulations. We consider results from the Global Timber Model (GTM), prepared for the Energy Model Forum 21 at Stanford University (Sohngen and Sedjo, 2006). This model was used in the previous analysis based on WITCH by Tavoni, Sohngen, and Bosetti (2007) and is also used by the U.S. Environmental Protection Agency for its analyses of international forest carbon provisions in proposed U.S. climate legislation. We also incorporate results from runs of the IIASA model cluster (Gusti et al. 2008), prepared for the U.K. Office of Climate Change as part of the recent Eliasch Review (2008).

The estimated opportunity costs of avoiding deforestation in the Brazilian Amazon are lower than those from the global models. One reason is that the global models incorporate price feedbacks, with avoided deforestation efforts raising the price of timber and agricultural commodities, thus making protecting deforestation more costly. Another reason is that Nepstad et al. (2008) consider revenues from sustainable forest management as a benefit from conserving forests, while the GTM and IIASA models model foregone timber harvests as a cost of forest preservation. These models also differ in the baseline (business-as-usual) levels of forestry emissions as well as the estimated costs and quantities of available reductions.[11] The varying baselines arise from differences in the underlying data on land use and carbon, assumptions over deforestation drivers, and regional coverage (see Kindermann et al., 2008, for a comparison of the global models). We account for these differences by adjusting the business-as-usual land-use emissions in WITCH to be consistent with each REDD scenario.

Finally, we note some limitations of the study. We do not consider other potentially significant forest sector mitigation opportunities from afforestation/reforestation and changes in forestry plantation management, which could be significant in both Annex 1 and tropical and non-tropical developing countries. For simplicity, we do not consider potential interactions between the forest and energy sectors, other than those mediated through the carbon market. Potential feedbacks between the climate and forests, which could affect both emissions and mitigation potential, were also beyond the scope of this study.

3. Policy Scenarios

The basic policy scenario draws from what appears to be most realistic for broad groups of countries, with industrialized countries adopting binding commitments to reduce emissions initially and developing countries accepting commitments at a later date. We model a scenario that stabilizes atmospheric concentrations around 550 ppmv CO_2 equivalent. This is at the less ambitious end of the 450-550 stabilization range considered by Stern (2008) as necessary to avoid dangerous human interference with the climate under the mandate of the UNFCCC. We are conservative in our assumptions about the targets that the global community may actually be able to agree upon as our interest is to explore how such targets could potentially be tightened with the aid of REDD. In addition, we are interested in evaluating the extent to which linking tropical forest mitigation with a global carbon market could delay or otherwise depress technological innovation in the energy sector. Less ambitious global targets reduce the need for emissions reductions and thus provide greater scope for detecting the potential suppression of key technologies, such as carbon capture and storage, often deemed strategically important in climate change discussions.

We assume that Annex 1 countries reduce emissions to 30% below 1990 levels by 2020 and 60% below 1990 levels by 2050. These targets are in the range of the EU's "shared vision" for industrialized countries, which proposes cutting emissions relative to 1990 levels by 20-30% by 2020 and 60-90% by 2050. The American Clean Energy and Security Act of 2009 (H.R.2454), sponsored by Chairmen Waxman and Markey and recently approved by the Energy and Commerce Committee of the US House of Representatives, proposes emissions caps for the U.S. equivalent to a reduction below 1990 levels of 1% by 2020 and 68% by 2050. Complementary requirements and additional potential reductions envisioned by the legislation increase the stringency to 17-23% below 1990 levels by 2020 and 71-77% by 2050 (Larsen and Heilmayr 2009). The long-term targets are the most important factor in providing incentives

[11] For Brazil, Nepstad et al. (2008) forecast a continuation of historic emissions of about 250 Mt/C per year. Incorporating these into the baseline land-use emissions in the WITCH model produces net global forestry emissions of 1.1 Gt/year in 2005 falling to 0.3 Gt/year by the end of the century. This compares to net global forestry emissions in the IIASA models of 1.5 Gt/year in 2005 falling to 0.6 Gt/year 2050. In contrast, the GTM model projects baseline net global emissions remaining roughly constant at 0.2 Gt/year throughout the century.

for technological R&D and investments in our modeling framework.[12] By considering Annex 1 reductions of 60% below 1990 levels by 2050, we consider the relatively less stringent range of the proposed long-term targets, thus providing greater scope for detecting any reductions in technological innovation resulting from possible market "flooding."

In our base case scenario, developing countries continue along their business-as-usual (BAU) emissions path until 2020, as modeled in other recent studies (e.g. Paltsev 2007) and the U.S. EPA in its climate policy analyses. After 2020, Africa continues with BAU while all other developing countries begin reducing to 1990 levels by 2050. After 2050, Annex 1 countries and all developing countries other than Africa continue reducing emissions gradually (about 65-75% below their BAU emissions). Restrictions on other greenhouse gases are allocated to regions in proportion to their CO2 share. This policy scenario produces radiative forcing around 3.5 W/m^2 and stabilizes atmospheric concentrations around 550 ppmv CO_2 equivalent.

Our basic policy scenario models a global market that is limited until 2020, such that Annex 1 countries can only buy up to 10% of their allocated emissions on the carbon market, and is unconstrained thereafter. This restriction mimics the constraints that have been proposed for EU and US carbon market designs. It is in line with the supplementarity limits allowing use of CDM credits only up to 10% of companies' obligations under the EU ETS. Similarly, the 1-billion ton limit on the use of international offsets in the recently proposed Waxman-Markey draft bill corresponds to about 14% of allowed US emissions through 2020. The modeled carbon market allows full flexibility of trading across gases, with permits derived from reductions in CO_2 emissions fungible with reductions in non- CO_2 gases on a GHG-equivalent basis.

Figure 1 shows what this basic scenario means in terms of global emissions, mitigation efforts of OECD and non- OECD countries, atmospheric GHGs concentrations and predicted increase in temperature. Estimates relative to the basic policy scenario are compared against estimates for the baseline (BaU) scenario. While emissions and GHG concentrations rise under BaU, producing a mean predicted value of warming close to 4º C by the end of the century, the policy scenario stabilizes concentrations around 550 CO_2 equivalent, and is estimated to limit the mean global temperature rise to less than 2.5º C below preindustrial levels. The IPCC identifies that constraining temperature rise to less than 1.6-2.6º C above preindustrial levels provides a significant reduction of climate risks, including melting of the Greenland Ice sheet and turning the terrestrial system into a net carbon source (IPCC 2007). OECD countries undertake the major share of global reductions domestically in the early years, when international trading is limited and developing countries do not have commitments to reduce emissions. Reductions within OECD countries continue in absolute terms until around 2075. Reductions in the non-OECD countries reach an equal total amount by about 2025 and become a steadily rising global share of emissions, representing more than twice the reductions in the OECD by the end of the century.

To examine the impact of linking REDD to the carbon market, we run variations of the basic policy scenario with and without availability of reduced deforestation as a mitigation option, using each of the

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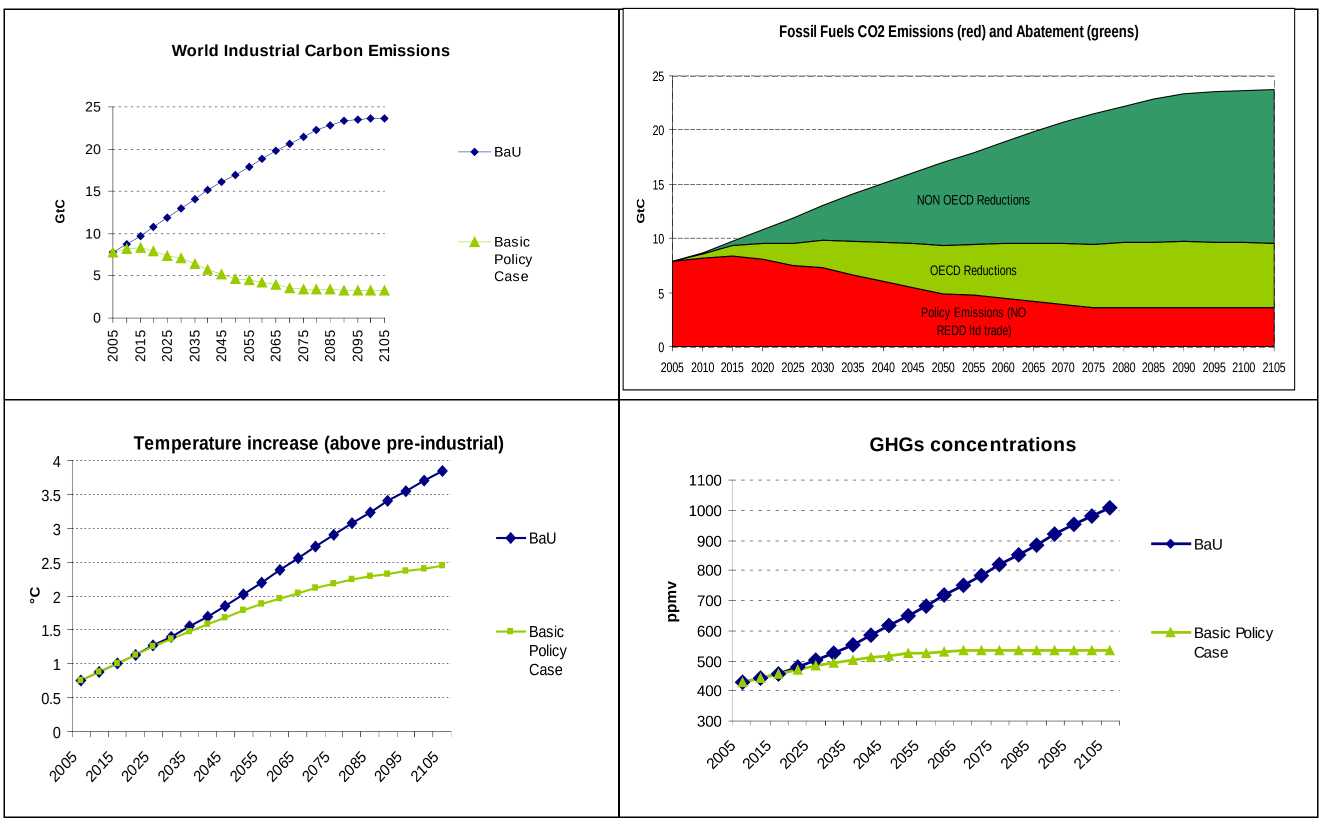
[12] In theory, short-term incentives are also important for driving innovation through learning-by-doing in WITCH. As discussed in the next section, WITCH estimates relatively low carbon prices in the first decades. This suggests our choice of the more stringent range of proposed 2020 targets is not critically driving technological change in our simulations.

three estimates of REDD costs and potential described in the previous section. In these scenarios, reduced emissions from deforestation are freely fungible with permits derived from mitigation in other sectors. We also consider the flexibility to trade credits across time, which most recent analyses of REDD and carbon markets do not consider. The role of banking is highlighted by running variations of each of our scenarios: one allowing for the flexibility of banking and the second where no banking is allowed.[13]

The IPCC emphasizes the value of near term mitigation in providing a global hedge against the need to take more stringent action in the future (Fisher et al. 2007). Along these lines, researchers have argued that the opportunity to avoid deforestation in the near term at relatively low costs has value as a "real option" that preserves flexibility if there is a need to increase the stringency of global climate policy in the future in response, for example, to new scientific information (Golub and Greenberg 2009). We explore this possibility through a scenario which continues as in the base case through 2050, at which point there is new information about the sensitivity of the climate system, requiring the global community to adopt a more stringent climate target. The more stringent target is assumed to require the strictest policy that WITCH predicts is feasible as of that point in time, which achieves GHG concentrations of 515 CO_2 equivalent by 2100. We run this scenario both with and without REDD and focus, for simplicity, on the REDD cost curves from IIASA.

Figure 1. Emissions and climate impacts under business-as-usual and climate policy without REDD



[13] Borrowing of future credits for use in early periods is technically possible in the model but is not observed in practice as carbon prices rise over time, making borrowing economically unprofitable.

4. Discussion of Results

The results of the analysis are summarized in Table 1. REDD represents a modest and declining source of overall global abatement, particularly when banking enables the world to take greater advantage of higher availability of REDD and other cost-effective opportunities in the early periods. The global models differ in terms of costs, quantities, and regional distribution but yield similar aggregate patterns of REDD. In the case with banking, for the GTM and IIASA models, respectively, REDD represents a 19.3% and 19.8% share of cumulative abatement by 2020, falling to 9.2% and 8.7% by 2050 and 4.1% for both models by the end of the century. In contrast, without banking, there are less than half as much foresty emission reductions over the first decades and somewhat less over the century, with REDD representing 3.2% and 7.9% of cumulative global abatement by 2020, 7.5% and 7.2% by 2050, and 3.5% and 3.6% by 2100 for the GTM and IIASA models, respectively.

When the supply of REDD is restricted to just Brazil, reducing deforestation emissions is still a significant source of abatement and actually represents a larger share of total abatement in the case without rather than with banking. This is because REDD from just Brazil is a relatively cost-effective source of abatement in the early years which, given its more limited scale, is largely pursued even without banking. In the Brazil case, REDD represents 5.6% (9.4%) 2.9% (3.1%) and 1.6% (1/6%) share of cumulative abatement by 2020, 2050, and 2100 with (and without banking).

Both banking and the availability of REDD shift forward the time profile of abatement, potentially providing greater atmospheric benefits by reducing the time that greenhouse gases remain in the atmosphere. For example, in the IIASA case without banking, 22.6% of abatement this century is achieved by 2050. In contrast, when there is banking, 24.1% and 23.9% of the modeled abatement this century is met by 2050 with and without REDD, respectively.

The effect of linking REDD to a global carbon market are to significantly and rapidly reduce global deforestation emissions (see the second variable reported in Table 1). In the banking cases, tropical deforestation emissions decline by an estimated 16% (Brazil), 72% (GTM), and 50% (IIASA) by 2019 and by 22% (Brazil), 88% (GTM), and 64% (IIASA) by 2049. When global REDD is modeled, global deforestation emissions decrease such that the global forest sector becomes a net sink (e.g., negative net emissions) by the middle of the century.

The basic policy without REDD results in Global World Product (GWP) losses of 2.5% and 1.8% at a 3% and 5% discount rate, respectively.[14] The added flexibility of banking lowers these losses to 2.1% and 1.6% at a 3% and 5% discount rate, respectively. Despite the restrictions on overall trading and the modest relative contribution to total global abatement, REDD is estimated to decrease the costs of meeting a global climate target, with the impact depending on the estimated potential and the availability of banking. In the no-banking case, overall policy costs for the century decline by 11%, 24%, and 22% based on the Brazil-only, GTM, and IIASA estimates, respectively. Irrespective of REDD, policy costs are lower when banking is allowed. With banking, REDD reduces the costs by 10%, 21% and 23% in the Brazil-only, GTM, and IIASA cases, respectively.[15] Focusing on the IIASA case, these results indicate

[14] These results are robust to the level of forestry emissions incorporated in the baseline.

[15] The gains in policy costs measured in discounted terms depend on the choice of the discount rate, even though only marginally, as a large part of the cost reduction accrues during the first part of the century. Here we are using a discount rate of 5%, but if we were to choose a 3% discount rate, gains would be increased to 11%, 21%, and 25% in the three cases with banking.

Table 1. Estimated cumulative impact of REDD on abatement share, deforestation emissions, and global policy costs, by time period

Variable (REDD scenario below)		2010-19	2010-49	2010-99
Cumulative Share of REDD in Global Abatement				
With Banking	Brazil Only	5.6%	2.9%	1.6%
	Global Timber Model	19.3%	9.2%	4.1%
	IIASA Model	19.8%	8.7%	4.1%
Without Banking	Brazil Only	9.4%	3.1%	1.6%
	Global Timber Model	3.2%	7.5%	3.5%
	IIASA Model	7.9%	7.2%	3.6%
Cumulative Reductions in Emissions from Deforestation				
With Banking	Brazil Only	-15.7%	-21.7%	-29.6%
	Global Timber Model	-72.2%	-87.8%	-90.9%
	IIASA Model	-50.3%	-63.9%	-68.4%
Without Banking	Brazil Only	-11.3%	-20.4%	-28.9%
	Global Timber Model	-4.9%	-64.3%	-78.1%
	IIASA Model	-8.2%	-47.6%	-59.9%
Cumulative Reductions in Loss of Gross World Product (GWP)[a]				
With Banking	Brazil Only	-7.2%	-8.5%	-9.9%
	Global Timber Model	-7.6%	-17.7%	-21.4%
	IIASA Model	-10.6%	-19.8%	-22.9%
Without Banking	Brazil Only	-6.9%	-7.8%	-11.1%
	Global Timber Model	-13.3%	-18.7%	-24.0%
	IIASA Model	-15.4%	-17.2%	-22.2%

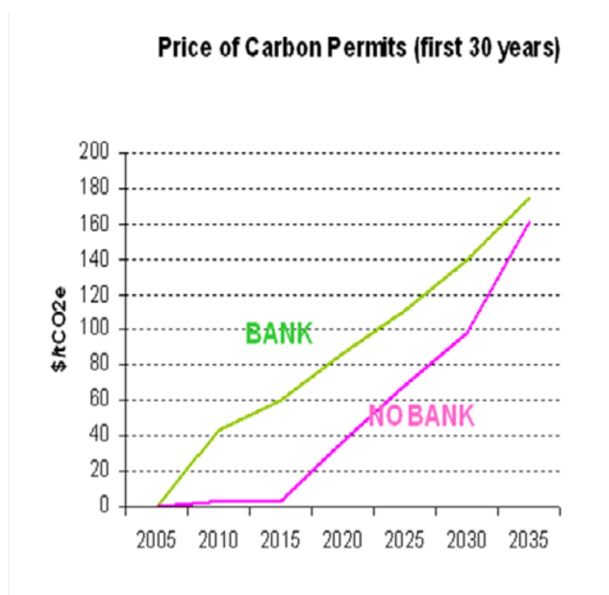
[a] Estimates are based on a 5% discount rate.

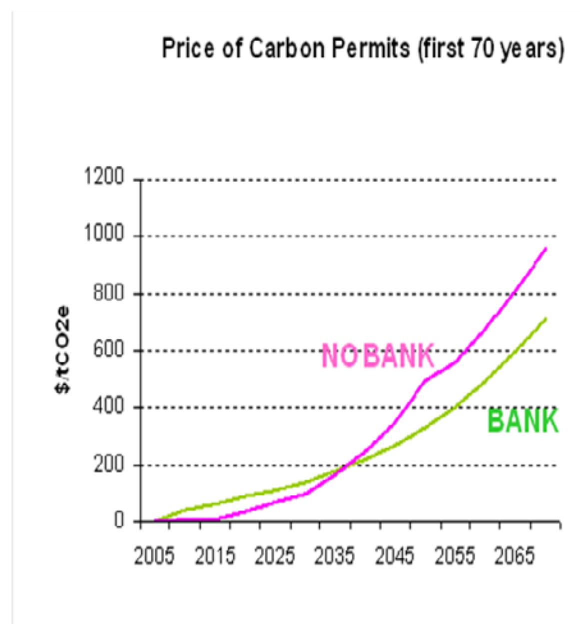
that REDD could enable additional reductions of at least 20 ppmv of CO_2-equivalent concentrations (about 0.2º C less warming over the century) with no added costs compared to an energy-sector only policy.

We explore the contribution of REDD for the scenario that implies new information becomes available in 2050 that calls for a more stringent reduction in global emissions. When no banking is allowed, REDD reduces the costs of the more stringent policy by 17% as only limited quantities of forest mitigation are available in the later years. In contrast, when banking is allowed, REDD reduces the costs of the more stringent policy by an estimated 28%. Having in mind the objective of preserving policy flexibility given scientific uncertainties over the long-term climate targets, REDD mitigation thus has an additional value especially when associated with the possibility of banking.

The contribution of Brazil-only is also notable as it is disproportionate to the modeled quantities of REDD abatement. While Brazilian REDD reduces costs by roughly half as much as the global estimates, total deforestation emissions reductions in the Brazil case are only about one third and 40% of the predicted REDD abatement in the global models by 2050 and 2100, respectively, in both the banking and no-banking cases. This suggests that the even a modest amount of REDD can generate significant cost savings by reducing the need to rely on the highest marginal cost abatement sources.

Figure 2. Projected impact of banking on the carbon price trajectory, no-REDD base case.





In the base case, with no REDD and without banking, the permit price is modeled to begin around $4/t$CO_2$ equivalent, rising sharply to $36 by 2020 and to almost $400 by 2050. In contrast, when banking is allowed, the price trajectory is flattened, with higher prices in the early years and lower prices in the later years (see Figure 2). In contrast to other models in which banking causes the price to rise at a constant rate of interest, this is not the case in WITCH as the rate of return on capital is determined endogenously in the model for each region and time period. With banking, the price rises to $87 over

2015-19 but only to $330 over 2045-49[16]. The availability of REDD mitigation moderates the level of prices, as reported in Table 2. In the no-banking case, REDD has negligible impacts on the price prior to 2020 as other abatement opportunities are relatively plentiful and the quantities of trading are restricted

Table 2. Estimated impact of REDD on carbon prices, by time period

Variable (REDD scenario below)		2015-19	2045-49	2095-99
Reductions in Price of Carbon:				
With Banking	Brazil Only	-7.8%	-7.9%	-11.3%
	Global Timber Model	-22.1%	-22.2%	-18.0%
	IIASA Model	-23.3%	-22.9%	-22.2%
Without Banking	Brazil Only	-0.1%	-11.0%	-12.3%
	Global Timber Model	0.0%	-25.7%	-21.5%
	IIASA Model	0.0%	-20.4%	-24.7%
Price of Carbon (\$/tCO_2eq.):				
With Banking	Brazil Only	56	247	1,063
	Global Timber Model	47	208	984
	IIASA Model	46	207	932
Without Banking	Brazil Only	3.5	307	1,118
	Global Timber Model	3.5	257	1,000
	IIASA Model	3.5	275	960

Note: Estimated reductions in the price of carbon are relative to the No REDD case.

[16] Estimates of stabilization costs computed applying WITCH are higher than those reported by IPCC (2007). Marginal abatement costs crucially depend on assumptions about availability and penetration of carbon free technologies in the electric and non electric sectors. This is particularly true for more stringent scenarios where almost complete decarbonization of the economy is required by the end of the century. In WITCH multiple carbon free alternatives are modeled for the electricity sector, whereas new technologies become competitive in the non electricity sectors only through large investments in R&D. In addition, the diffusion processes for new technologies are modeled in order to mimic the time required in order to undertake the extensive infrastructural changes. Finally, WITCH features a non-cooperative representation of knowledge creation and diffusion processes. All these factors are at the basis of these higher estimates.

However, the price falls by an estimated 11%, 26%, 20% in 2045-49 and 12%, 22%, and 25% in 2045. - 99 in the Brazil-only, GTM, and IIASA cases. When banking is available, prices are higher from the beginning due to greater demand for abatement. This "when-flexibility" allows REDD to more consistently lower the carbon price trajectory throughout the century. Indeed, with banking, REDD lowers prices by about 8-23% in 2015-19, just as in 2045-49 and 2095-99 (see Table 2).

Our results indicate modest and varying effects of REDD on energy technology, R&D and innovation investments (see Table 3). The effect of REDD on innovation and technologies investments is twofold. On one side, REDD makes it possible to attain the stabilization target while slightly relaxing the pressure to reduce energy emissions (cumulatively allowing for 2%, 8% and 10% more emissions from the energy sector over 2010-2049 in the Brazil only, GTM, and IIASA REDD scenarios). As a result, linking REDD to the carbon market is estimated to decrease investments in the development of renewable (wind and solar) and nuclear energy sources, as well as in energy-intensity R&D. Investments in R&D on non-electric technologies also decline in the banking cases. The decreases are modest if we consider that both with and without REDD the climate policy induces a substantial increase in all these investments with respect to a no policy case (ranging from 60 to 80% for solar/wind and energy-intensity R&D). Investments in integrated gasification combined cycle (IGCC) plus carbon capture and storage (CCS) technologies are actually estimated to increase slightly (0.5-1.4% in the banking case and 0.1 to 0.7% in the no banking case) with the introduction of REDD, as these technologies are not completely carbon free and are slightly favored under less stringent restrictions on the energy sector's emissions.

Table 3. Technology investments for the period 2010-2049, with REDD versus without REDD.

Scenario for REDD		Change in Total Low Carbon Technology Investments			Change in Total Energy R&D Investments		
		IGCC and CCS	Nuclear	Solar and Wind	Energy Intensity	Non-Electric	Total
With Banking	Brazil-only	0.5%	-1.1%	-2.0%	-8.2%	-2.2%	-4.2%
	Global Timber Model	1.4%	-3.2%	-5.8%	-2.8%	-0.5%	-1.5%
	IIASA Model	1.4%	-6.1%	-6.3%	-7.5%	-4.1%	-4.6%
Without Banking	Brazil-only	0.7%	-1.8%	-3.2%	-4.8%	1.6%	-1.5%
	Global Timber Model	0.7%	-4.0%	-7.9%	-9.9%	1.6%	-4.2%
	IIASA Model	0.1%	-6.6%	-6.9%	-9.4%	1.1%	0.5%

The second effect is related with fossil fuel prices. This again derives from the greater flexibility in the required reduction of fossil fuel consumption that REDD allows. As a result, prices of fossil fuels, particularly oil, are slightly higher under the REDD scenarios, increasing the relative profitability of investments in alternative carbon free technologies in the non-electricity sector (and boosting the R&D required to make this alternative technology competitive). The optimal response to the introduction of

REDD across all scenarios is a small (1-2%) increase in non-electric breakthrough technologies R&D spending rather than a reduction in the cases without banking.

For the 2010-2049 period, the introduction of REDD decreases total cumulative energy R&D expenditures by 4.2% (1.5%) in the Brazil-only case and by 1.5% (4.2%) in the IIASA case, with (and without) banking. and by 4.6% (+0.5%) in the GTM case, with (and without) banking. These changes in research funding have relatively small impacts on the development and deployment of technologies often considered critical for the mitigation of climate change. In particular, total estimated quantities of carbon sequestered through CCS technology over 2010-2049 remain unchanged with the introduction of REDD in the scenarios with banking. In the scenarios without banking, REDD slightly delays the deployment of CCS, leading to 1% (Brazil), 4% (GTM), and 5% (IIASA) less carbon sequestered through CCS over 2010-2049, and 4%, 5%, and 7% more carbon sequestered through CCS over the next 34 years, respectively.[17]

Table 4. Quantities and values of global carbon market transactions

Scenario		2010-29	2010-49	2010-29	2010-49
Scenario without REDD		*(billion t CO_2 eq.)*		*(US$ billions/year)*	
With Banking	IIASA Model[a]	1.7	1.4	681	1,412
Without Banking	IIASA Model[a]	0.5	0.7	119	918
Scenario with REDD		*(billion t CO_2 eq.)*		*(US$ billions/year)*	
With Banking	Brazil Only	1.8	1.5	682	1,348
	Global Timber Model	2.1	1.7	667	1,306
	IIASA Model	2.3	1.8	716	1,347
Without Banking	Brazil Only	0.5	0.7	114	797
	Global Timber Model	0.5	0.8	97	773
	IIASA Model	0.6	0.9	116	876

[a] The results from the IIASA model are representative of the other cases without REDD. While the results vary across scenarios due to differences in the estimated forestry emissions baselines, the differences are negligible.

[17] In the IIASA cases with maximum stringency after 2050, REDD decreases total R&D by 4% (3%), with and without banking. In these cases, REDD decreases CCS sequestration by 6% with banking and increases CCS sequestration by 1% without banking over 2010-49.

We also examine the volumes and values exchanged internationally through the carbon market. Banking consistently raises the financial flows by raising the carbon price and increasing the quantities exchanged in the early years. In the cases without REDD, banking increases average carbon market volumes by 261% over 2010-29 and by almost 100% over 2010-49. At the same time, banking increases carbon market values by 480% over 2010-29 and by 55% over 2010-49.

Table 5. Average annual value of deforestation emissions reductions, by region

Scenario for REDD		2010-2029			2010-2049		
		Africa	Asia	Latin America	Africa	Asia	Latin America
		(US$ billions/year)			*(US$ billions/year)*		
With Banking	Brazil Only	0.0	0.0	50.6	0.0	0.0	104.1
	Global Timber Model	21.5	42.6	40.1	39.2	71.2	73.1
	IIASA Model	13.9	25.9	110.9	19.0	30.8	166.6
Without Banking	Brazil Only	0.0	0.0	19.7	0.0	0.0	90.2
	Global Timber Model	7.0	13.1	12.1	31.7	55.6	58.7
	IIASA Model	3.9	6.6	33.2	14.6	21.1	133.0
		(% share)			*(% share)*		
With Banking	Brazil Only	0%	0%	100%	0%	0%	100%
	Global Timber Model	27%	34%	38%	28%	32%	40%
	IIASA Model	9%	17%	74%	9%	14%	77%
Without Banking	Brazil Only	0%	0%	100%	0%	0%	100%
	Global Timber Model	27%	35%	38%	29%	31%	40%
	IIASA Model	9%	15%	76%	9%	13%	79%

Note: Estimates are the average annual value of deforestation emissions reductions in each region based on the global market price.

While REDD increases the quantities of carbon exchanged internationally under all scenarios, the financial flows over the carbon market remain relatively constant in the cases with and without REDD because the increase in volumes is counterbalanced by the decrease in price (see Table 4). Over 2010-29, REDD increases the quantities of carbon exchanged by 8-35% with banking and 3-19% without banking. In contrast, the average annual value of carbon market transactions ranges from -3% and +4% of the no-

REDD case in the banking scenarios and falls by 5 to 9% in the no-banking cases. Over 2010-49, REDD is estimated to have a more modest effect on the carbon market volumes and the decrease in price dominates the increase in quantities in all scenarios. The average estimated value of annual market transactions, with (and without) banking, is estimated at $1.3 ($0.8-$0.9) trillion with REDD compared to $1.4 ($0.9) trillion without REDD over 2010-49.

While the values exchanged internationally stay steady or decrease modestly, REDD increases the domestic mitigation opportunities in developing countries, which are not only exported but used to satisfy domestic commitments after 2030 (see Table 5). The Latin America region is estimated to receive the greatest share of overall value from reducing deforestation. Of course, when only Brazil sells credits, Latin America receives all of the REDD value, estimated with (and without) banking at $51 ($20) billion/year over 2010-29 and $104 ($90) billion/year over 2010-49. When REDD is global, the average yearly value of deforestation reductions rises to $104-$150 ($32-$44) billion over 2010-29 and $183-$216 ($146-$169) billion over 2010-49, with and (without) banking. Latin America receives about 40% (GTM) and 77% (IIASA) of the gains, while Asia receives 31-35% and Africa 27-29% across the different global scenarios.

5. Conclusions

This paper analyzes the effects of linking REDD to a global carbon market using a dynamic integrated assessment framework, which explicitly models induced technological change in the energy sector. We incorporate expected patterns of global participation as well as institutional features considered likely, such as limits on initial international trading and permit banking. Our research confirms that integrating REDD into global carbon markets can provide powerful incentives for the preservation of tropical forests while lowering the costs of global climate change protection and potentially enabling agreement on more stringent targets. The effect of linking REDD to a global carbon market are to significantly reduce global forestry emissions, reducing tropical deforestation emissions by an estimated 22% (Brazil), 88% (GTM), and 64% (IIASA) by the middle of the century, in the banking cases.

Despite initial limitations on REDD trading, introducing REDD lowers the total costs of the stabilization policy over this century by an estimated 10-23% depending on whether only Brazil or all tropical countries participate. We estimate that REDD could enable additional reductions of at least 20 ppmv of CO2-equivalent concentrations (about 0.2º C less warming) with no added costs compared to an energy-sector only policy. When banking is allowed, the cost savings from REDD are magnified if there is a need to increase the stringency of global climate policy in the future in response, for example, to new scientific information. This suggests that REDD has an important value in preserving policy flexibility.

Our results are broadly consistent with those reported in earlier studies, although they provide a more detailed description of possible outcomes and are more conservative in the number of forestry mitigation options that can be credited on the market and in the share of emission targets that countries can cover with REDD and other international credits during the first phase of the agreement. To recall, previous studies estimated the savings in costs from REDD in the range 30-50% for 2020 and 2030. We find cost savings in the range 7-20% prior to 2050, depending on the scale of REDD and the possibility of banking. Our lower estimated costs savings may be due to our modeled restrictions on REDD trading prior to 2020 as well as differences in the forestry models and climate targets. In terms of the price of carbon, previous models that have not considered the possibility of banking estimate reductions in 2020 of 0-20% when the REDD market is limited and as high as 45% when the market is not restricted. For 2015-19, based on our limited trade assumption, we estimate negligible carbon price impacts, in line with the results from Eliasch (2008). When banking is considered, we estimate the price would decline by 7-23%, depending on whether only Brazil or all tropical forest countries participate. Our global REDD results are somewhat higher than the 13% estimate from the comparable scenario of Piris-Cabezas and Keohane (2008), likely as a result of differences in the estimated supplies of REDD.

While REDD increases the volumes of carbon transacted in the marketplace, the reduction in price means that international financial flows overall remain stable. Developing regions, particularly Latin America, gain the increased value of forestry mitigation opportunities. Annual REDD values reach $183-$216 billion/year over 2010-49 under the global REDD scenarios with banking. Our results also indicate that REDD generally reduces, by 1-10%, investments in renewable and nuclear technologies as well as research and development in energy-intensity technologies through 2050. The results vary depending on the specific technology as well as the scenario and the availability of banking. While the higher range of our estimates are consistent with the prior findings of Tavoni, Sohngen and Bosetti (2007), our results with banking indicate a higher carbon price such that REDD has a smaller estimated impact on investments and R&D into alternative energy technologies.

While REDD generally decreases investments into alternative energy technologies, a notable exception is investments in integrated gasification combined cycle (IGCC) plus carbon capture and storage (CCS) technologies, which are estimated to increase slightly (0.1-1.4%) as a result of REDD. We find that REDD provides flexibility that lowers demand for mitigation in the energy sector, thus allowing slightly larger investments in fossil fuel technologies. This in turn marginally raises fossil fuel prices, especially oil, increasing the relative competitiveness of alternative carbon free technologies in the non-electric sector. These results support to the findings of Golub et al. (2008) that REDD policies could actually boost investments in CCS and other clean energy technologies, though we examine different mechanisms than the risk hedging considered in their analysis.

Our assessment of the impacts of REDD in a global carbon market considered mitigation from avoided deforestation only, without considering other possible sources of forest sector abatement, such as afforestation/reforestation, as well as other sources of land-based abatement from changes in agricultural practices. Incorporating these additional opportunities would likely lead to additional cost savings, while lowering the relative impact of REDD. Future research could further examine the value of REDD in reducing costs and maintaining flexibility under different second-best policy settings, where there are delays in global abatement actions or incomplete global participation in a climate stabilization program.

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