The Role of the Forest in Climate Policy

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Doctoral thesis 2016

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Umeå Economic Studies No. 927
Department of Economics, USBE, Umeå University
ISBN: 978-91-7601-462-2
ISSN: 0348-1018

Cover photo: Map depicting atmospheric carbon uptake from plants, created by NASA/Goddard Space Flight Center Scientific Visualization Studio
Electronic version available at http://umu.diva-portal.org/
Printed by: Print & Media at Umeå University
Umeå, Sweden 2016

To My Family

Abstract

This thesis consists of an introductory part and four papers related to the optimal use of forest as a mitigation strategy.

In **Paper [I]**, I develop the FOR-DICE model to analyze optimal global forest carbon management. The FOR-DICE is a simple framework for assessing the role of the boreal, tropical, and temperate forests as both a source of renewable energy and a resource to sequester and store carbon. I find that forests play an important role in reducing global emissions, especially under ambitious climate targets. At the global level, efforts should focus on increasing the stock of forest biomass rather than increasing the use of the forest for bioenergy production. The results also highlight the important role of reducing tropical deforestation to reduce climate change.

In **Paper [II]**, I develop the FRICE to investigate the role of two key efforts to increase the stock of forest biomass, namely, afforestation and avoided deforestation. FRICE is a multi-regional integrated assessment model that captures the dynamics of forest carbon sequestration in a transparent way and allows me to investigate the allocation of these actions across space and time. I find that global climate policy can benefit considerably from afforestation and avoided deforestation in tropical regions, and in particular in Africa. Avoided deforestation is particularly effective in the short run while afforestation provides the largest emissions reductions in the medium run. This paper also highlights the importance of not solely relying on avoided deforestation as its capacity to reduce emissions is more limited than afforestation, especially under more stringent temperature targets.

In **Paper [III]**, we investigate how uncertainties linked to the forest affect the optimal climate policy. We incorporate parameter uncertainty on the intrinsic growth rate and climate effects on the forest by using

the state-contingent approach. Our results show that forest uncertainty matters. We find that the importance of including forest in climate policy increases when the forest is subject to uncertainty. This occurs because optimal forest response allows us to reduce the costs associated with uncertainty.

In **Paper [IV]**, we explore the implications of asymmetries in climate policy arising from not recognizing forest carbon emissions and sequestration in the decision-making process. We show that not fully including carbon values associated with the forest will have large effects on different forest controls and lead to an increase in emissions, higher carbon prices, and lower welfare. We further find, by investigating the relative importance of forest emissions compared to sequestration, that recognizing forest emissions from bioenergy and deforestation is especially important for climate policy.

Keywords: climate change; integrated assessment; forest carbon sequestration; forest bioenergy; avoided deforestation; afforestation; uncertainty; dynamic modeling; DICE; RICE

Acknowledgements

I am deeply grateful to my supervisors Runar Brännlund and Tommy Lundgren. Your advice and guidance have truly been fundamental to my research. Thank you for always having your office open and taking the time to read and give insightful comments on my work.

Writing these acknowledgments makes my mind wander back to how it all started. Runar, without your inspiration and encouragement I would not have ventured to the world of academia. All the way back from my undergrads, and throughout these years, I have learned much from you and hope to continue doing so in the future. I am also deeply indebted to Kenneth Backlund for introducing me into the world of modeling, the world that was to become a part of my everyday life. Runar and Kenneth, without your early encouragement I would not have entered this journey, and this thesis would not exist.

Over these years, I have also received valuable support from other researchers at the department of economics and CERE. Thank you all for creating such a great work environment. I am also very grateful for all the people I got to know during my time at UC Berkeley and Paris School of Economics. Many thanks for all the feedback and inspiring discussions. I consider myself very privileged to have had the opportunity to write this thesis at three rather contrasting institutions. I strongly believe that my research has benefited greatly from this experience.

I would also like to thank the former and current PhD-students in Umeå for all the great times both on and off work. You truly made this experience great! Naturally, I am also very thankful for my wonderful friends outside of academia who lift my gaze far beyond economics.

Finally, I would like to thank my family to whom this dissertation is dedicated. Your endless love and support made this thesis possible.

Paris, April 2016

Mathilda

This thesis consists of a summary and the following papers:

[I] Eriksson, M. (2015). The role of the Forest in an Integrated Assessment Model of the Climate and the Economy. *Climate Change Economics*, 6(3). Copyright © 2015 World Scientific Publishing Company.

[II] Eriksson, M. (2016). Mitigating Climate Change with Forest Climate Tools. *CERE Working Paper,* 2016:05

[III] Eriksson, M., and Vesterberg, A. (2016). When Not in the Best of Worlds: Uncertainty and Forest Carbon Sequestration. *CERE Working Paper,* 2016:04

[IV] Eriksson, M., Brännlund, R., and Lundgren, T. (2016). Pricing Forest Carbon: Implications of Asymmetry in Climate Policy. *CERE Working Paper,* 2016:06

1 Introduction

Anthropogenic climate change is unlike any other public policy challenge that we have faced. In the words of Wagner and Weitzman (2015), climate change is a problem that is "almost uniquely global, uniquely long-term, uniquely irreversible, uniquely uncertain, and certainly unique in the combination of all four."

At the time of writing this introduction, the concentration in the atmosphere of the heat-trapping gas carbon dioxide (CO_2) is 403 ppm.[1] Given business as usual trends, we could be in the 750 ppm region by the turn of the century. This level of CO_2 was last experienced three million years ago when temperatures were regularly 4°C above preindustrial levels (Pagani et al., 2010). As predicted by climate models, this levels of CO_2 could once again lead to a temperature increase of a similar magnitude (Rogelj et al., 2012). At this temperature range the related climate effects are likely to be so disruptive that they may pose an existential threat to our species, or at the very least, alter where and how we live.[2]

At the root of the climate change problem is the fact that it does not matter where carbon is being emitted. Climate change is a global externality, where the benefit of activities that create emissions are local while the impact of emissions on temperature are global. At the country level, the problem is further compounded by the fact that low-income countries that have contributed the least to emissions are usually those most vulnerable to its negative effects (Tol, 2009). Additionally, climate change is a particular vexing problem because of its long term horizon. This occurs because the lifetime of some of the heat-trapping gases is in tens of thousands of years (Archer, 2005). Thus current actions might lock us onto specific paths that are irreversible on human time scales (IPCC, 2013). Which in turn implies that the bulk of the climate related effects

[1] Monthly mean CO_2 for January, 2016 (Last updated: March 7, 2016). See NOAA http://www.esrl.noaa.gov/gmd/ccgg/trends/global.html

[2] See Stern (2013) for a review of the damages that are likely to occur at 4°C.

will affect future generations which are not physically present today to influence our policy choices.

This global, long-term, and irreversible problem is further compounded by deep uncertainties, both on the scientific and economic side. These include uncertainties about the relationship between: emissions and accumulation of heat-trapping gases, the concentration of these gases and temperatures, higher temperatures and the related climate effects, climate effects and damages, and damages and human behavior. This behavioral response is at the heart of the problem because our actions, both regarding mitigation and adaptation, will ultimately determine the total cost of climate change, and will partly determine how these costs are shared across countries and generations.

This thesis focuses on the role of forests in controlling climate change. Forests play a crucial part in the global carbon cycle. The growth of forest biomass can reduce global carbon concentrations by absorbing carbon from the atmosphere and storing it in its biomass. Conversely, decreasing the forest biomass leads to carbon emissions. Globally the stocks of carbon in the forest are decreasing due to the loss of forest biomass. Deforestation and forest degradation is today the second largest anthropogenic source of global carbon emissions, after use of fossil fuels (IPCC, 2007).

This thesis consists of four papers. My aim with these papers is to contribute to the understanding of the role of the forests as a mitigation strategy in global climate policy. In the first two papers, I develop global frameworks, one single regional and one multi-regional, to investigate how forest climate tools, such as avoided deforestation, afforestation, and forest bioenergy can be used in conjunction with traditional carbon abatement strategies. In paper three, I investigate along with Vesterberg, how the optimal climate policy is affected by uncertainties linked to the forest. In the last paper, I investigate along with Brännlund and Lundgren, the consequences of asymmetric carbon policies.

The rest of this introductory part of the thesis is outlined in the following way: Section 2 provides a short overview of integrated assessment modeling (IAM), which have been influential in guiding the decisions of policymakers. Section 3 presents an introduction to the DICE/RICE family of IAMs on which I base my frameworks. Section 4 provides a summary of the four papers of the thesis.

2 Integrated Assessment Models (IAMs)

The primary purpose of Integrated assessment models (IAMs) is to improve our understanding of different policy options to tackle climate change. To assess climate policies we need to combine environmental science, that quantifies the relationship between emissions and their impact on temperature, with economics, that quantifies the value of climate damages and the cost of reducing emissions. By quantifying these values in a single framework, these models can be a useful pedagogical device that allows us to think about the relationships between the climate, the economy, and climate policy. Ultimately, IAMs can be used to inform policymakers about different courses of action.

In fact, these models have been very influential over the last decades. Since externalities, even global ones, can be resolved by pricing the damage caused by the externality. Policymakers attention has focused on a single metric produced by these models: the social cost of carbon. This figure represents the marginal cost of carbon emissions along the optimal emissions path. In practice, it is also the level at which a Pigouvian tax capable of solving the climate change problem should be set.

A particularly influential set of estimates of the social cost of carbon are those derived by the US government through the Interagency Working Group on Social Cost of Carbon. Initial estimates by the workgroup place the social cost of carbon in the order of $20 per ton, with those figures being recently revised to roughly $40 per ton. The working group derives its estimates by averaging the results from three well

known IAM's. These include two welfare maximization IAM's: the Dynamic Integrated model of Climate and the Economy model (DICE), and the climate Framework for Uncertainty, Distribution, and Negotiations model (FUND). As well as a simulation IAM: the Policy Analysis of the Greenhouse Effect model (PAGE).

Broadly, welfare maximizations IAM's can be characterized by two blocks: the economic growth block which determines how production leads to emissions, and the climate model which relates emissions to the concentration of heat-trapping gases, and in turn to increases in temperatures. These blocks interact with each other through two functions. The abatement function which generally refers to the cost and effectiveness with which policy curbs emissions, and the damage function which models how increased temperature leads to economic damages.

Characterizing the DICE and FUND at a more detailed scale, reveals a number of fundamental differences: from the algorithm used to the solve maximization problem, to the time steps and the time horizon taken into account. Perhaps, more substantially the models vary considerably in the way they capture damages. While DICE takes an aggregated approach where temperature affects output, FUND models damages at the sector level.

Simulation IAM's, like PAGE which is primarily concerned with modeling uncertainty, take a different structure. Their starting point is to assume that the path of emissions and the related changes in temperature are exogenous. They do not aim to determine the optimal policy mix, as they do not maximize welfare. Instead, these models aim to estimate the cost under various scenarios.

While there are many more IAM's worth noting, a detail survey of the literature exceeds the scope of this introduction. Interested readers are instead directed to Stanton et al. (2009) who review 30 of the most commonly used models.

In essence, IAM's are our best approximation to a very complex problem.

These models are the product of a number simplifying assumptions, and reflect the judgment of each author on how best to summarize the evolving scientific consensus on a wide range of environmental and economic issues. Accordingly, we cannot expect these models to produce estimates of key metrics, such as the social cost of carbon, along a narrow interval. Instead, we must interpret each estimate together with the assumptions on which the model is built. Frequently debated key assumptions include the discount rate, exogenous growth of production, construction of the damage function, and the role of uncertainty.

Perhaps the most discussed assumption in IAMs is the discount rate, which concerns how we value the well-being of future generations (e.g., Ackerman et al. (2009); Stern (2007); Portney and Weyant (1999); Arrow et al. (1996)). Given the long time horizon that characterizes the climate change problem, the discount rate is a critical assumption with large impacts on the estimates of the social cost of carbon. As the bulk of the cost of climate change takes place in distant future, a higher discount rate generally leads to lower rates of mitigation in IAMs. Another related assumption that has not received as much attention is how we value consumption between regions. Most multi-regional IAMs use Negishi weights (Stanton, 2011). These weights equalize the marginal utility of consumption across regions preventing any possible Pareto improvement from income redistribution (Negishi, 1960).

Another crucial debate as pointed out by Stern (2013), is that most IAM's combine exogenous drivers of growth with damages functions that are naturally limited by our lack of knowledge about damages at 5°C or more. In fact, our gaps in knowledge exist at even lower temperatures. For example, Nordhaus accentuates that we should be cautious when extrapolating damages beyond 3°C. The very influential work of Weitzman (2009, 2012) illustrates paths forward to better model the uncertainty related to the damages created by climate change. Nonetheless, is still the case that current models do not take into account damage from omitted factor such as mass migrations or conflict (Stern, 2013). All in all,

the combination of exogenous growth and possibly weak damages functions, suggest that IAM's predictions of the cost of carbon might be too conservative.

These debates, and more broadly the contingency of results on the ability of models to adequately summarize current scientific knowledge, has recently sparked some constructive criticism. Despite the IAM's shortcomings, best outlined by Pindyck (2013), we should follow the example of environmental sciences and continue to develop the economic side of IAM's. When pushing forward, however, it is my view that we should remember that IAM's are primarily designed to inform policy. Given their purpose, it is important that the models not become too complex and risk being viewed as a black box by policymakers. One constant challenge of IAMs is finding the balance between detail/accuracy and simplicity/transparency. Rather than attempting to capture all features of reality and provide detailed predictions, we should instead prioritize capturing only the most essential features and prioritize transparency. With this thought in mind, I have chosen one of the most well know and well-studied families of IAM's as the basis for the models I develop in this thesis.

3 The DICE and RICE models

The DICE/RICE family of models is one of the earliest and most well-known within the IAM literature. The DICE (Dynamic Integrated model of Climate and the Economy) was first developed and described by Nordhaus (1994) and the RICE (Regional Integrated model of Climate and the Economy) was first developed by Nordhaus and Yang (1996). These models have subsequently been updated and extended by William Nordhaus (Yale University) but also by many other researchers. In addition to the models being publicly available since their early development, the popularity of the models largely stems from their theoretical transparency. Compared to many other IAMs, the relationships within the

DICE/RICE are relatively simple making the models computationally and empirically tractable. This is especially true for the DICE model, which has gained the largest attraction because of its simplicity and straightforward optimization problem as a globally aggregated model. While both DICE and RICE are designed as welfare optimization models with essentially the same structure, the regional disaggregation in RICE creates a significant larger model. The global economy in the latest versions of the RICE model is composed of 12 different regions. The regions are chosen based on their regional or economic similarity, some of the regions consist of a single country while other regions consist of many countries.[3]

The DICE/RICE models are based on the foundations of neoclassical economic growth theory. In these models, economies can reduce consumption today via investment in order to increase the capital stock and future consumption. DICE/RICE expands this traditional neoclassical theory by including the greenhouse gas concentration as negative environmental capital. By investing in abatement to reduce greenhouse gas emissions, economies can reduce consumption today in order to avoid future loss in consumption from climate damages.

A climate block, consisting of a set of geophysical equations, describes how emissions via the carbon concentration increase atmospheric temperature. The temperature increase, in turn, affects regional economic output through a damage-output function and, in later vintages of the models, a sea-level rise damage function. Economic output comes from a Cobb-Douglas production function of labor, capital, and energy. Energy needed in the production is either based on fossil fuel, which create emissions, or on non-carbon based technologies, which represent abatement. Technological change is exogenous both for the total factor productivity and the carbon-saving technological change. In the RICE model, there are regional specific structures for economic output, labor, emissions,

[3]The 12 regions in the RICE-2010 are: Africa, China, EU, Eurasia, India, Japan, Latin America, Middle East, Russia, USA, Other High-Income countries, and Other Non-OECD Asia.

damages, and abatement.

Designed as policy optimization models, the DICE/RICE models finds the optimal path of abatement and investment that maximize the economic objective function. The objective function refers to the present value of all future utilities from consumption. The welfare of each generation increases with the size of the population and per capita consumption, with diminishing marginal utility of consumption. The elasticity of the marginal utility of consumption together with the discount rate affects the relative importance of different generations. In the RICE model, each region has a welfare function and the objective of the model is to maximize the sum of these welfare functions, weighted by region-specific weights. This is done in the RICE model by solving for the optimal path of abatement and investment in each region.

A key determinant of welfare is the efficiency with which societies can reduce emissions. Total emissions in the DICE/RICE models are composed by exogenous emissions from land, and endogenous emissions from the production of energy from fossil fuels. In this setup, emissions can only be directly reduced by abatement, that is, production of non-carbon based energy. Forests have so far not been explicitly included in these models in spite of the key role that they can play to reduce emissions and thus to mitigate climate change.

3.1 The FOR-DICE and FRICE models

In order to investigate the role that forests can play in climate policy, I extend the DICE-2007 (Nordhaus, 2008) and RICE-2010 (Nordhaus, 2010) models by including a number of key strategies through which forests can mitigate climate change. My work attempts to accurately capture some of the key features of forests, while maintaining the simplicity and transparency of the frameworks. The result is FOR-DICE and FRICE.

In the FOR-DICE model, developed in Paper [I], I explicitly model the

stock of growing forest biomass. The global biomass is divided into tropical, temperate and boreal forest according to its ecological characteristics. I explore the use of forest biomass both as a source of energy and as a resource to sequester and store carbon. The forest controls of the model are harvest of biomass to produce energy and avoided deforestation in the tropics, which makes the emissions from land of the DICE-2007 model endogenous. In the later version of the FOR-DICE, used in Paper [III] and [IV] of this thesis, I extend the forest controls to include the possibility of increasing forest land through afforestation.

In the FRICE model, developed in Paper [II], I include forest controls to increase the sequestration and storage of forest carbon by including avoided deforestation and afforestation. These forest controls are chosen at the regional level, where the regional division of the world follows the one in RICE-2010. In contrast to the FOR-DICE, which models the effects of forest controls through the stocks of forest biomass, the effects of the forest controls in FRICE are directly modeled in terms of emissions and sequestration. For regions with emissions from land of the RICE-2010 model, the forest control avoided deforestation make these emissions endogenous. The forest control afforestation sequestrates carbon over time following regional sequestration curves.

In what follows, I provide further details on the models, the contribution, and the results of each of the papers.

4 Summary of the papers

Paper [I]: The Role of the Forest in an Integrated Assessment Model of the Climate and the Economy

The objective of this paper is to investigate the role the global forest can play to mitigate climate change. To do this, I develop the FOR-DICE model. The FOR-DICE extends the DICE-2007 (Nordhaus, 2008) by incorporating the global boreal, temperate, and tropical forest biomass.

These three types of forest biomass are modeled as endogenous state variables, controlled by avoided deforestation and bioenergy harvest. This simple framework allows me to model the global forest both as a source of renewable energy and as a carbon sink. The dynamics of each type of biomass follows a logistic growth function formulation. The parameters regarding the forest biomass stocks, carbon, and harvest are primarily based on data from the Food and Agriculture Organization of the United Nations (FAO, 2010). Energy values are derived from data from the International Energy Agency (IEA (2014c), IEA (2014a), IEA (2014b)) and the United Nations Statistical Division (UNSD, 2014). Baseline deforestation in FOR-DICE follows the path of emissions from land in the DICE-2007 model. The cost of avoiding this baseline deforestation is derived from estimates by Kindermann et al. (2008).

The results show that forests can play an important role in reducing global emissions, and increasingly so under more stringent climate policies. In accordance with previous literature, I find that avoiding deforestation in the tropical forest is a cost-efficient instrument to mitigate climate change. My main result at the global level shows that policy efforts should focus on increasing the stock of growing forest biomass rather than increasing the use of forest biomass to produce energy. This occurs because the release of carbon associated with the use of biomass is not offset by avoided fossil fuel emissions. However, the results differ between forest zones due to differences in the carbon content of biomass, the bioenergy efficiency, and the growth rate of the biomass. Bioenergy harvest is increasing for the temperate forest while decreasing for the boreal and tropical forest. Consistent with previous literature, these results highlight that forest bioenergy should not be treated as carbon neutral. Policies that promote the production of forest bioenergy without taking the dynamics of the carbon flows into account may lead to negative climate effects. By and large, my findings show that forest can be an important tool to contribute to emission reductions but should be viewed as a complement to mitigation efforts to produce non-carbon-based energy.

Paper [II]: Mitigating Climate Change with Forest Climate Tools

In this paper, I develop the FRICE model to analyze how the optimal paths of forest climate tools are related to the stringency of the global temperature target. More specifically, FRICE estimates the potential role, and spatial allocation, of two key forest climate tools, namely, afforestation and avoided deforestation. This multi-regional integrated assessment model is an extension of the RICE-2010 model (Nordhaus, 2010).

The baseline carbon emissions from land in the RICE-2010 model are used as approximations of the regional baseline deforestation paths. The costs of avoiding these deforestations are derived from estimates by Kindermann et al. (2008). The climate benefit of avoiding deforestation occurs directly through the reduction of baseline emissions from deforestation. The benefit from afforestation, on the other hand, takes place over time through sequestration from forest growth. This carbon accumulation over time is described by a sigmoidal function. The marginal costs of afforestation are derived from the total agricultural production value per hectares from the Global Agro-Ecological Zones (GAEZ v3.0) (Fischer et al., 2012) geospatial dataset.

The main result of this paper is that avoided deforestation and afforestation provide a cost-effective way to enhance global climate policy. However, the geographical allocation of these tools varies greatly due to different costs and forest characteristics between regions. The largest potential for cost-effective avoided deforestation and afforestation lies in the tropical forests of Africa, Asia, and Latin America. This paper also shows that avoided deforestation provides the largest short-run benefits while afforestation is most effective in the medium to long run. The results further demonstrate that stringent temperature targets will increase the relative importance of using afforestation to reduce emissions, as the potential to reduce emissions with avoided deforestation is limited

and will be quickly exhausted.

Paper [III]: When Not in the Best of Worlds: Uncertainty and Forest Carbon Sequestration

Many aspects of the dynamics of the forest and its interaction with climate change are still unknown. Despite these gaps in knowledge, uncertainty has largely been neglected in studies investigating the role of forests to mitigate climate change. In this paper, we explicitly model some of the key uncertainties linked to the forest and investigate their impact and importance in climate change policy.

We use the FOR-DICE (Eriksson, 2015) framework and implement parameter uncertainty with the state-contingent approach. In this approach, drawings from probability distributions of unknown parameters create possible states of the world. As it is not known which of these possible states that will occur, the optimal policy under uncertainty is found by maximizing the sum of utility for each of these possible states. In this paper, the unknown parameters are directly linked to the growth of forest biomass and to climate change effects on forests growth and geographical distribution.

We analyze the importance of including uncertainty by comparing the results from the optimal climate policy under uncertainty to the results derived from a deterministic optimization. Our overall result shows that uncertainty matters. Not taking uncertainty into account will lead to misleading carbon prices and non-optimal policies. Interestingly, we also find that including the forest in climate policy becomes more important when the forest is subject to uncertainty. Moreover, recognizing the forest in climate policy makes us more resilient to uncertainty, as optimal forest policy response allows us to reduce the costs associated with uncertainty. Without the forest controls in the set of mitigation tools, uncertainty will instead lead to high costs of reducing emissions by a large increase in non-carbon energy.

Paper [IV]: Pricing Forest Carbon: Implications of Asymmetry in Climate Policy

Currently, most countries with an active climate policy have focused their efforts on providing incentives to reduce the use of fossil fuels. These policies create asymmetric incentives for the use of different sources carbon, and can lead to an inefficient climate policy. The purpose of this paper is to examine the implications of asymmetric carbon policies that arise from imperfect accounting of forest carbon. To do this, we use an extended version of the FOR-DICE model and investigate two types of asymmetric carbon policy regimes. Compared to the symmetric carbon policy, the forest controls in the asymmetric regimes are set without, or with only partially, including the carbon values associated with the forest. In the first regime, we investigate the asymmetry between pricing fossil carbon and forest carbon, that is, policymakers take into account carbon emissions from fossil fuels but not emissions or sequestration from forests. In the second regime, we investigate the asymmetry that occurs when policymakers, in addition to fossil fuel emissions, only take into account either forest carbon emissions or sequestration from changes in forest biomass.

We show that the distortion in costs and benefits that arise under the asymmetric carbon policies leads to inefficient levels of forest controls and lower welfare. Overall, the results demonstrate that not recognizing forest emissions induce the largest deviation from the optimal levels of bioenergy harvest and avoided deforestation, while not recognizing sequestration induce the largest discrepancy for afforestation. Among the asymmetric carbon policies that we explore, the highest levels of total emissions, the highest carbon prices, and the lowest welfare, arise when policymakers neither recognize emissions or sequestration from forests. Specifically, not including the emissions or sequestration from forests in the decision-making process will lead to levels of bioenergy harvest that are too high, and to levels of afforestation and avoided deforestation that are too low. Results from the second policy regime indicate that

the welfare cost of not recognizing forest emissions are higher than not recognizing sequestration in climate policy.

We also provide a back of the envelope calculation on the magnitude of the required taxes and subsidies under the symmetric carbon policy. This calculation shows that the optimal subsidy payment for sequestration will exceed the optimal tax revenue from forest emissions for all forest types. However, the overall subsidy can be financed when including the optimal tax revenue from fossil fuels.

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