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This thesis is comprised of two manuscripts that relate to forest-based management strategies in the context of market-based climate change mitigation policies. The work questions the appropriateness of a singular focus on carbon sequestration given the albedo effect and its possible countervailing climatic impacts. Through a review of salient literature and via new examples, it is demonstrated that the concept of radiative forcing should instead be employed to express on a more consistent basis the relative climatic impacts of carbon sequestration and albedo. Specifically this work proposes that accounting frameworks measure the climatic benefits of any forest management activity in terms of “carbon equivalent.” Chapter 1 introduces the albedo effect and briefly describes market-based policies and extant forest management strategies. Chapter 2 explores how landowner behavior may change under a tax/subsidy system based upon a “carbon equivalent” rather than a “carbon only” approach, and in addition investigates the possibility of managing explicitly for albedo. Chapter 3 considers instead a cap-and-trade system, examining how forest offset efficiency may be diminished because of the albedo effect, and offers policy guidance for offset design moving forward. Chapter 4 summarizes the results of these findings.

Radiative Forcing and Forest Climate Policy

by

Matthew P. Thompson

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

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CONTRIBUTION OF AUTHORS

Dr. Darius Adams was integral to all components of manuscript work, from recommending and synthesizing relevant literature to facilitating analyses to editing written work. Dr. John Sessions initially alerted the primary author to the nature of the albedo effect, and co-authored Chapter 2 in an editorial capacity. Dr. K. Norman Johnson co-authored Chapter 3, in particular helping to refine the policy recommendations and assisting with editing. Manuscripts associated with Chapters 2 and 3, at the time this thesis was submitted, were in the process of peer review.

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1 Introduction

1.1 Forest Climate Policy and Management

Forests continue to receive attention as a means of mitigating climate change due to their ability to sequester carbon and reduce atmospheric greenhouse gas concentrations. Though there is some debate about whether forest-based carbon sequestration is cost effective (e.g., van Kooten et al. 2004; Sohngen and Mendelsohn 2003), most generally agree that forest sequestration is competitive with other abatement measures and may play a significant role in national and global climate mitigation strategies (e.g., Tavoni et al. 2007; Lubowski et al. 2006; Boyland 2006; Richards and Stokes 2004). Pacala and Socolow (2004), for instance, include forest management in their global "wedge" strategy to stabilize atmospheric CO2 concentrations, combining reduced tropical deforestation with afforestation to achieve an annual reduction of 1 Gt C by the 50th year of implementation. Stavins and Richards (2005) estimate that a national forest-based carbon sequestration program could offset U.S. net carbon emissions by up to one-third, at costs similar to emissions reduction programs.

Forests are unique as a component of climate mitigation because they can provide numerous co-benefits such as clean water, wood products and wildlife habitat. Sequestering additional carbon through sustainable forest management therefore has become a recommended policy objective (Ruddell et al. 2007). Of course, forests cannot provide climate benefits if they are lost to conversion or cannot adapt to climate change. Thus retaining forest cover and promoting resiliency in forests are also important forest policy objectives (Ruddell et al. 2007). A common proposal is to assign market values to ecosystem services in order to more accurately reflect the suite of public benefits that forests provide and to incentivize forest landowners to manage in order to provide those benefits. This and other available policy instruments will be discussed in the next section. Below I briefly discuss forest management strategies for climate mitigation.

There exist various mechanisms by which forests can reduce atmospheric greenhouse gas concentrations. Opportunities for mitigation in the forest sector include reducing emissions (e.g., substituting wood products for other energy-intensive materials, reducing risk of catastrophic wildfire), enhancing sinks (e.g., afforesting marginal agricultural land, reducing deforestation, improving forest management), and reducing emissions and enhancing sinks simultaneously (e.g., substituting short-rotation biomass for fossil fuel energy, increasing utilization efficiency, planting trees in urban areas) (Birdsey 2006; Birdsey et al. 2000). Here I focus on land management opportunities for enhancing sink capacity of forests; forests are generally better at storing carbon than other land uses (Salwasser 2006). One primary way to achieve this goal is to increase the area under forest cover, via afforestation of agricultural lands and/or reducing forest losses to alternative land uses.

Alternatively, management of existing forests can be modified to promote sequestration. Improving forest management is the most cost-effective means, in the short-term, to sequester additional carbon (Birdsey et al. 2000). Actions to enhance forest carbon storage in actively managed forests include fertilization, pest and fire management, adoption of low-impact harvesting practices, reforestation, and alteration of harvest quantity and timing (Murray et al. 2000). In particular, rotation length, amount of live biomass harvested, and amount of detritus removed by slash burning have significant impacts on carbon storage, with rotation length being the most important factor (Harmon and Marks 2002). Extending the rotation length allows trees to grow larger, thereby storing more carbon, and pushes harvest emissions into the future. Additionally, forests managed on longer rotations accumulate more soil organic matter and litter, and tend to on average house more carbon than forests managed on short rotations (Krankina and Harmon 2006).

1.2 Policy Instruments to Encourage Forest Carbon Sequestration[1]

There exist a range of available policy instruments for promoting sequestration in forests, which vary in terms of cost-effectiveness, whether the government or private individuals exert control over private actions, and whether the government or private

[1] Unless otherwise stated, much of this section reviews material from Richards et al. (2006)

individuals bear the cost of those actions. Here I discuss four tools that can be used to achieve environmental protection and to induce changes in forest management: government production, command and control, practice-based incentives, and results-based incentives. Figure 1 summarizes these tools according to control and costs. Another way to conceptualize these tools is as rungs on a ladder, where private landowners are increasingly involved and given more control as one moves up the ladder (Figure 2). Costs are generally kept lowest when private landowners have the most control over their actions. That fact combined with a strong undercurrent of property rights may explain why most attention in the policy arena, at least nationally, has been focused on market-based policies where private landowners control their own actions and bear those costs.

At the lowest rung, government production, policies could aim to either affect emissions on federally owned land or to generate and disseminate information that would benefit private landowners. The latter is actively occurring on a variety of fronts, including for instance the U.S. Department of Energy 1605(b) program, which provides guidelines and a voluntary registry where forest activities may be registered (Birdsey 2006). The U.S.D.A. Forest Service also provides material support in terms of freely available publications and on-line resources. In terms of affecting emissions, the best opportunities likely lie in reducing wildfire risk in western national forests and promoting biomass utilization. Government production is associated with low monitoring and enforcement costs, the burden for which falls upon the taxpayers. Though the current stock in national forests is large, possibilities to actively manage to increase the net carbon flux are low (legal and/or economic roadblocks), as is the possibility to expand the forested land base through acquisition. Because of this, government production is likely to be paired with complementary policies influencing private landowners.

Under command and control, the government would institute mandatory emissions reduction standards, and emitters who could not meet those standards would be penalized. The Clean Water Act is an example of federal command and control legislation, wherein emitters of point-source pollution must meet end-of-pipe standards.

There are no national regulations of private forest management, though many states have forest practice regulations. Conversely some states, such as those in the timber producing southeast region, instead opt to promote voluntary best management practices (BMPs). Command and control is unpopular because it can result in inefficient allocations of resources, can discourage research and innovation, and is viewed by many as an unnecessary intrusion into free enterprise. Costs to government include administrative and monitoring costs, and private landowners incur opportunity costs from adherence to regulations. The cost-effectiveness of forest regulations in terms of emissions reductions is difficult to assess, in part because it requires prediction of landowner behavior in the absence of regulations, and in part because emissions reductions may be a co-benefit of policies implemented for other objectives.

Practice-based incentives promote conservation-oriented management. Typically this is achieved through the provision of services such as cost sharing, land rental, and technical assistance. Policymakers can choose to target landowners for assistance based upon financial or environmental need. Financial targeting seeks landowners who in theory would not have been able to afford promoted practices absent financial assistance. Environmental assistance conversely targets landowners based upon the environmental state of their land, whether it be in need of restoration or worthy of preservation. Estimating the benefits is challenging because of uncertainty in attributing carbon results to particular programs, and of questions over permanence (i.e., how long will the landowners continue to implement the encouraged practices). The burden of paying for results-based incentives falls upon taxpayers.

Results-based incentives provide the greatest flexibility to private actors, ideally minimizing costs. The government effectively creates a market where carbon has a price and it becomes costly to emit. The idea is that to avoid costs from emissions, polluters would invest in emissions reduction technology, shift to other technology, or reduce production. Market incentives include carbon subsides, taxes, and credits. A hybrid tax/subsidy program is also possible, wherein tax revenue could offset subsidy expenditures. The award of credits would occur in conjunction with a broader cap-and-trade program. Table 1 provides a comparison of these market approaches. Tax/subsidy systems are considered to be more efficient approach, but have minimal political support. Cap-and-trade systems on the other hand have broad consensus and appear to be an eventuality at the regional and possibly national level.

Under a tax-based system the expectation is that polluters would incur emissions reduction costs up to the point where the marginal costs of doing so equal the price of carbon. Over time the carbon price may be increased to encourage further emissions reductions. The primary advantage to a tax system is price certainty. This provides an important long-term signal to investors considering costly emissions reduction technology, such as clean burning coal plants. The primary disadvantage is no guarantee of emissions reductions. Another disadvantage is increased energy costs to consumers, though tax revenue can be used to offset income or other taxes for those sectors of the population most adversely impacted.

Under a cap-and-trade system the government sets an emissions threshold and distributes allowances to polluting entities in capped sectors. Those entities that don't use all of their allowances may sell their allowances on the open market to other polluters in need of extra allowances. Over time the number of allowances given out is reduced, lowering the emissions threshold. Marketable permits enable companies that produce more value per unit of pollution to buy the pollution rights from those who produce less value; this enables pollution rights to flow to those who value them most. This approach can help ensure the highest value possible (in terms of goods and services) for the level of pollution that will be permitted. In contrast to a tax system, cap-and-trade systems have greater certainty regarding emissions reductions but can exhibit price volatility. Additionally, there are issues of equity in how allowances are distributed between sectors, and whether they are auctioned or given away. As with taxes, under a cap-and-trade system consumers would face higher energy costs, though revenue raised from government auctions could be reinvested in social programs.

For the remainder of this thesis I focus on two market-based policy tools, a tax/subsidy and cap-and-trade. More specifically, I focus on the intersection of forest management and said policies. To achieve either policy, frameworks would need to, at a minimum, identify an official carbon accounting standard, and in the case of cap-and-trade, establish an official registry for carbon credits (Binkley et al. 2002). Traditionally the objective of a market-based policy directed at forest management has been to increase the net forest carbon flux, by incentivizing sequestration in forests and wood products. As I will point out, however, such a narrow policy objective could result in unintended and/or undesirable climatic consequences. A growing body of research is suggesting that forest management strategies for climate change mitigation should focus on more than just greenhouse gas reduction.

1.3 Radiative Forcing, Forests, and the Albedo Effect

Forests generally are darker than bare or agricultural land, and consequently absorb more solar radiation, possibly warming the surrounding region. This is known as the albedo effect. The albedo of an object is the extent to which it reflects radiation, defined as the ratio of reflected to incident electromagnetic radiation. The climatic impacts of carbon sequestration, surface albedo changes, and other processes can be expressed in terms of radiative forcing, defined as the net change in global irradiance (W m^{-2}) due to changes in external climate drivers (IPCC 2007). Forests can exert a negative radiative forcing through carbon sequestration, but they can also exert positive forcing by reducing surface albedo.

Where the albedo effect has been incorporated into research, management implications can differ from what would otherwise be pursued under a sequestration maximization objective. Bala et al. (2007) simulated large-scale deforestation experiments and reported global cooling due to changes in albedo and evapotranspiration. Specifically, deforestation resulted in warming in tropical regions, essentially no change in temperate regions, and cooling in boreal regions. Since a primary goal of mitigating (or avoiding) climate change is to pass on our natural heritage to future generations, it would make little sense to pursue deforestation as a mitigation strategy (Caldeira 2007). Nevertheless, the results of Bala et al.'s (2007) highly unrealistic scenarios have real implications: afforestation projects intended for climate-change mitigation may not have the expected impacts if implemented at high-latitudes. Similarly, Gibbard et al. (2005) reported that simulated global afforestation/reforestation would increase global mean temperatures, and stated that creating tree plantations in non-tropical locations may yield undesirable results. Randerson et al. (2006) applied the concept of radiative forcing to investigate the possible impacts of boreal forest fire on climate warming, and found that future increases in fire may not accelerate global warming. Loss of canopy from fire can lead to increased snow exposure and increased albedo, resulting in negative annual forcing exceeding positive radiative forcing from carbon emissions. Earlier studies found that historic land-use changes, such as deforestation, increased surface albedo, which could have led to cooling observed prior to the 20th century (Govindasamy et al. 2001; Brovkin et al. 1999).

Betts (2000) developed a methodology incorporating the concept of radiative forcing to express the relative climatic impacts of forest sequestration and albedo. Specifically he calculated the equivalent change in terrestrial carbon stock that would result in the same global forcing from establishment of a coniferous plantation. From this he estimated net equivalent carbon stock changes from forestation over the course of one management rotation. Reduction in surface albedo from forestation exerts a positive forcing just like releases of carbon from wildfire or harvest. Thus forestation of bare or agricultural land can have comparatively worse climatic impacts despite the increased sequestration capacity; this is especially true in snowy regions where absent forest cover the land would stay white and reflect sunlight for much of the year. Thus forestation could in some circumstances lead to net equivalent emissions. Results from global simulations suggest that many boreal forests exert a warming rather than cooling influence, and that the climatic benefits of temperate forests are dampened by the albedo effect.

Thus location and climate play very important roles in determining a forests relative ability to contribute to climate change mitigation. van Minnim et al. (2008) investigated the effectiveness of sequestration in forest plantations, and stated that because of biophysical effects, plantations should not be established at high latitudes if climate mitigation is the sole objective. Schaeffer et al. (2007) compared biomass and carbon plantations in terms of their respective climate impacts via albedo and carbon sequestration. They found that the albedo effect can offset sequestration benefits and questioned the efficacy of extra-tropical carbon plantations as a mitigation strategy. Betts et al. (2007) likewise suggested that carbon plantations outside of the tropics could be less effective than expected or even counterproductive.

In sum, forests in boreal and high-latitude temperate regions may actually exert a warming influence relative to other land-uses such as agriculture, because the cooling effect of carbon sequestration is more than offset by the warming effect of shortwave solar radiation absorption. In light of this, Gibbard et al. (2005) argue that more research is necessary before forest carbon storage is deployed as a strategy for mitigating global warming. Proper consideration of both carbon cycle and albedo effects may lead to more informed and more effective forest management policy.

Marland et al. (2003) explored four policy options ranging from exclusion to a complete integrated assessment recognizing all climate implications stemming from land-use and land-change, noting that with current tools the latter option remained elusive. The second option, complete fungibility between sources of carbon flux, is consistent with UNFCC and the Kyoto Protocol but does not capture the full climatic impacts. The third and recommended (at least in the interim) option considered radiative forcing rather than greenhouse gas concentrations. The authors suggested that "region-specific 'discount coefficients' might be derived for a first-order attempt to adjust changes in carbon stocks according to their simultaneous effect on surface albedo and their net effect on the Earth's radiative balance," (p. 153) a method not dissimilar from the carbon equivalency calculations of Betts (2000).

1.4 Moving Forward

This thesis investigates the potential implications for forest management from explicitly considering radiative forcing in the development of market-based climate mitigation policies. I effectively adopt Betts' (2000) methodology, wherein the positive radiative forcing from surface albedo results in equivalent greenhouse gas emissions. The current scientific level of understanding regarding the radiative forcing impacts of surface albedo is medium-low (IPCC 2007). Continued research will improve our preliminary understanding of the albedo effect and will enable more explicit investigations into forest management and climate change implications. Thus my research focuses on developing meaningful frameworks for forest climate policy analysis and offering suggestions for how policy could incorporate radiative forcing, rather than promoting specific policy directives based upon theoretical results.

In Chapter 2 I consider a tax/subsidy scheme based upon radiative forcing, and investigate its impacts on even-aged forest management. Specifically I consider three management decision variables: species choice, regeneration effort, and rotation age. A fundamental assumption of the chapter is that species choice and regeneration effort can substantively affect a stand's climatic impacts by altering the time patterns of both carbon flux and equivalent emissions due to changes in surface albedo. I employ Faustmann rotation equations to determine the optimal rotation age under various assumptions about the aforementioned variables as well as varying timber and carbon prices, discount rates, and functional forms for an albedo-equivalent emission equation. Chapter 2 illustrates how landowner behavior would change under an alternative tax/subsidy scheme not based exclusively on carbon. Further, the chapter illustrates how climate mitigation policies based exclusively on carbon could be more costly than expected or ineffective.

In Chapter 3 I explore the role of forest offsets under a cap-and-trade scheme. Though sequestration in forests and forest products provides a useful tool for reducing atmospheric greenhouse gas concentrations, there are yet many challenges to successful implementation of a forest offset program. Challenges that have been identified and discussed in the literature include the adoption of proper accounting standards that include risk and the role of wood products, establishment of baseline scenarios against which to compare additional sequestration, allocation of credit among stakeholders, and leakage. An additional challenge that has not yet been discussed in detail is how the efficacy of forest-based offsets may be impaired by the countervailing effect of surface albedo. I propose policy frameworks that account for radiative forcing rather than just carbon, in particular the adoption of "carbon-equivalent" accounting methods.

Lastly, Chapter 4 summarizes the results of Chapters 2 and 3.

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Figure 1.1: Policy instruments arranged by who controls the details of activities and who bears the financial burden of those actions (Richards 2004). Highlighted in gray is the focus of this thesis, results-based incentives.

	Private Control	**Government Control**
Private Pays	Results-based incentives	Command and Control
Government Pays	Practice-based incentives	Government Production

Figure 1.2: Policy Tool Ladder (Richards et al. 2006)

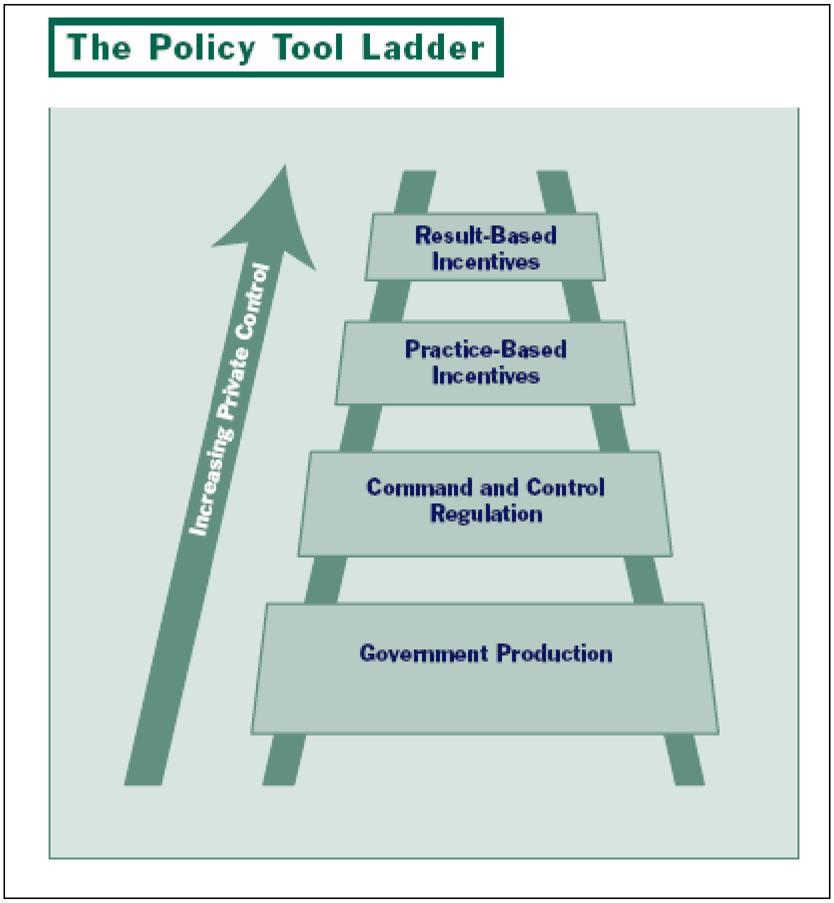

Table 1.1: Comparison of Results-based Policy Tools (Richards et al. 2006)

Policy Tool	**Description**	**How GHG Goal is Set**	**Who Bears the Financial Burden**
Subsidies	Monetary payment or tax advantage in $/ton to any landowner	Price-based target ($/ton)	Government/ taxpayers
Taxes	A levy in $/ton on releases of terrestrial carbon	Price-based target ($/ton)	Private sector
Credits	Award of credit in tons of credit per tone of sequestered carbon	Quantity-based target on fossil fuel sources of emissions (tons)	Depends upon specific program design

2 Radiative Forcing and the Optimal Rotation Age

2.1 Abstract

Forests help mitigate climate change by sequestering atmospheric carbon. However, boreal and high-latitude temperate forests may also contribute to global warming due to the albedo effect. The relative effects of carbon sequestration and albedo can be quantified in terms of radiative forcing. We present a stylized, stand-level analysis to determine the optimal rotation age when considering a tax/subsidy scheme based on radiative forcing and the notion of equivalent carbon emissions. Additional management decision variables considered include species choice and regeneration effort, since these can impact the albedo effect. We demonstrate analytically that the optimal rotation length is likely shortened when albedo-related equivalent emissions are incorporated, relative to a policy based only on carbon. Empirical results indicate that rotation ages do decrease relative to a "carbon only" policy, and approach the traditional (timber only) Faustmann rotation age as equivalent emission rates increase. Our results suggest that forestation does not necessarily provide climatic benefits in all circumstances, and that, at the margin, other opportunities for carbon reduction (e.g. abatement), or pursuing forestation in other locations, become more attractive.

2.2 Introduction

Forests continue to receive attention as a means of mitigating climate change due to their ability to sequester carbon and reduce atmospheric greenhouse gas concentrations. Recent research, however, suggests that forest management strategies for climate change mitigation should focus on more than just greenhouse gas reduction (e.g., Bonan 2008). Forests generally are darker than bare or agricultural land, and consequently absorb more solar radiation, possibly warming the surrounding region. This is known as the albedo effect. The albedo of an object is the extent to which it reflects radiation, defined as the ratio of reflected to incident electromagnetic radiation. Forests in boreal and high-latitude temperate regions may actually exert a warming influence relative to other land-uses such as agriculture, because the cooling effect of carbon sequestration is more than offset by the warming effect of shortwave solar radiation absorption. In light of this, Gibbard et al. (2005) argue that more research is necessary before forest carbon storage is deployed as a strategy for mitigating global warming. Proper consideration of both carbon cycle and albedo effects may lead to more informed and more effective forest management policy (Marland et al. 2003).

This paper examines the impact of the albedo effect on the optimal Faustmann rotation when sequestered carbon has value. We describe the nature of the albedo effect and its measurement in terms of equivalent carbon sequestered in, or emitted from, a stand. Theoretical rotation age effects are examined in the context of a carbon tax/subsidy system. We also explore how other management decision variables, specifically species choice and regeneration effort, may affect equivalent sequestration potential and the subsequent impacts on optimal rotation age. An empirical illustration of rotation age changes is developed for the case of a coastal mixed-conifer stand in British Columbia. A final section discusses the policy implications of our findings.

2.3 The Albedo Effect

Carbon sequestration and the albedo effect can impact the Earth's climate via radiative forcing, defined by IPCC (2001) as: "an externally imposed perturbation in the radiative energy budget of the Earth's climate system," measured as W / m^2. Forests can exert a negative radiative forcing through carbon sequestration, but they can also exert positive forcing by reducing surface albedo. Because of this, Gibbard et al. (2005) conclude that, in high-latitudes, forests likely have a net warming effect on the Earth's climate.

Where the albedo effect has been incorporated into research, management implications can differ from what would otherwise be pursued under a sequestration maximization objective. Bala et al. (2007) simulated large-scale deforestation experiments and reported global cooling due to changes in albedo and evapotranspiration. Specifically, deforestation resulted in warming in tropical regions, essentially no change in temperate regions, and cooling in boreal regions. Since a primary goal of mitigating (or avoiding) climate change is to pass on our natural heritage to future generations, it would make little sense to pursue deforestation as a mitigation strategy (Caldeira 2007). Nevertheless, the results of Bala et al.'s (2007) highly unrealistic scenarios have real implications: afforestation projects intended for climate-change mitigation may not have the expected impacts if implemented at high-latitudes. Other research has reached similar conclusions (e.g., van Minnim et al. 2008; Betts et al. 2007). Gibbard et al. (2005), for instance, reported that simulated global afforestation/reforestation would increase global mean temperatures, and stated that creating tree plantations in non-tropical locations may yield undesirable results. Randerson et al. (2006) applied the concept of radiative forcing to investigate the possible impacts of boreal forest fire on climate warming, and found that future increases in fire may not accelerate global warming. Loss of canopy from fire can lead to increased snow exposure and increased albedo, resulting in negative annual forcing exceeding positive radiative forcing from carbon emissions. Earlier studies found that historic land-use changes, such as deforestation, increased surface albedo and could have led to cooling observed prior to the 20th century (Govindasamy et al. 2001; Brovkin et al. 1999).

Betts (2000) developed a methodology incorporating the concept of radiative forcing to express the relative climatic impacts of forest sequestration and albedo. Specifically, his method can be used to determine the change in terrestrial carbon stock that would be equivalent to a change in surface albedo resulting from a transition from cropland to forestland. The first step is to simulate the shortwave radiative forcing due to local albedo changes as a result of land conversion, and then calculate the change in atmospheric CO2 concentration that would result in the same forcings as those wrought by local albedo changes. This permits one to estimate the contribution of a new coniferous plantation to global forcing, F, as a function of ΔC, the change in global-mean atmospheric CO2 concentration. Next the change in terrestrial carbon stock (ΔCT) is calculated that would give the same global forcing as the change in atmospheric CO2 levels. By combining equations, one can calculate the change in terrestrial carbon stock

(ΔCT) that would result in the same global forcing as that from the albedo effect of a new plantation (F). Betts labeled this equivalent change (in terms of radiative forcing) in carbon stock stemming from afforestation as the emissions equivalent of shortwave forcing (EESF). Thus, the effects of albedo and carbon sequestration can be expressed in comparable terms, with radiative forcings from albedo changes expressed as changes in equivalent carbon stock.

The equivalent changes in carbon stock are considered emissions because transition to forest lowers surface albedo and exerts positive radiative forcing, just like releases of carbon from wildfire or harvest. Betts (2000) estimated albedo forcings in terms of carbon stock change for temperate and boreal regions over the course of one management rotation and assuming a transition to dense coniferous plantations. The highest EESF values were observed in boreal forest regions, especially those with long durations of snow-cover, where prior to forestation cropland would otherwise have had a higher albedo and reflected more incident shortwave radiation. EESF is therefore a relative term that describes not the emissions equivalent from existing forest, but from the land-use transition to forest. Assuming that bare soil has similar albedo to that of cropland, EESF calculations can provide a rough estimate for the relative impacts of reforestation following harvest. As a plantation ages, albedo declines to an asymptote, F rises and the equivalent carbon stock change grows. We define A(t) to be the cumulative albedo-related equivalent carbon emissions per unit area of the stand, where t is the stand age. We expect $A' > 0$.

Thus, this paper investigates the potential implications of explicitly considering radiative forcing in the development of climate change mitigation strategies for actively managed forests. Although other studies have investigated strategies to reduce greenhouse gas concentrations via forest management, we are not aware of any that consider surface albedo changes as a result of land management. Perhaps closest, Marland et al. (2003) proposed, but did not compute, region-specific factors to “adjust changes in carbon stocks according to their simultaneous effect on surface albedo and their net effect on the Earth’s radiative balance.” (pg. 153) We draw from the work of

Betts (2000) and Marland et al. (2003) to develop stand-level analyses that more fully account for the climatic impacts of forests and forest management.

2.4 Forest Management and Mitigation Strategies

In the context of active forest management, enhancing the sink potential of forests is perhaps the most common objective of researchers. In the short-term, improving forest management is considered the most cost-effective means to sequester additional carbon (Birdsey et al. 2000). Actions to enhance forest carbon storage in actively managed forests include fertilization, pest and fire management, adoption of low-impact harvesting practices, and alteration of harvest quantity and timing (Murray et al. 2000). Rotation length in particular can have significant impacts on carbon storage (Harmon and Marks 2002). Extending the rotation length allows trees to grow larger, thereby storing more carbon, and pushes harvest emissions into the future. Forests managed on longer rotations accumulate more soil organic matter and litter, and tend on average to house more carbon than forests managed on short rotations (Krankina and Harmon 2006). Extending rotations could also yield additional value from higher quality wood products.

At the stand level, Hoen (1994), van Kooten et al. (1995), and Hoen and Solberg (1997), among others, have investigated the impact of carbon tax and subsidy schemes on the optimal rotation age for even-aged management. In these models landowners are paid a subsidy for periodic carbon uptake in biomass and taxed at release (harvest and subsequent decay). The Faustmann models developed are essentially variations on the Hartman (1976) model, which includes non-timber benefits. All other things being equal, as the value of carbon increases so does the optimal rotation age.

In general, where economic incentives to manage for carbon are incorporated into models, extending rotation age is an expected result, as Murray (2003) demonstrates. Im et al. (2007) simulated a carbon tax/subsidy system similar to that described above for private forests in western Oregon, and reported that average rotation age increased. Gutrich and Howarth (2007) likewise found rotation ages extended when including social benefits of carbon storage in a model applied to timber stands in New Hampshire.

Chladná (2007) presented a real options model for determining the optimal rotation age under uncertainty in both future wood and carbon prices. Unlike the aforementioned studies, Chladná found rotation periods were extended only under constantly high carbon prices, indicating the opportunity cost of prolonging harvest will be incurred only if the landowner is sure of financial benefit from sequestration.

2.5 Carbon and Equivalent Carbon Accounting

Although numerous approaches for carbon accounting exist, here we consider the discounting method (Richards and Stokes 2004). With the discounting method the time of carbon capture is important. Future carbon captured is discounted to the present using the social rate of time preference (SRTP) to create a metric known as present tons equivalent (PTE). Discounting future carbon allows for climatic benefits to be expressed on a consistent basis, and has been advocated for evaluation of forestry decisions (Murray 2003; Fearnside et al. 2000; Richards 1997). PTE of carbon of a stand harvested at age T with complete carbon release is calculated as:

$$PTE = \int_0^T CS'(t)e^{-\lambda t}dt - CS(T)e^{-\lambda T} \qquad (1)$$

where λ represents the SRTP, CS(t) the cumulative carbon sequestered at time t (t C / ha), and CS'(t) the rate of carbon uptake (t C / ha / yr).

How harvested biomass is utilized can have significant effects on carbon flow accounting and can impact the rotation decision (Stavins and Richards 2005). Wood products can provide long-term carbon storage, thus reducing taxable emissions. Perez-Garcia et al. (2005) estimated that 50% of harvested wood becomes lumber with an assumed service life of 80 years. It might then be transferred to a waste disposal site with some carbon loss, although in modern landfills lumber appears to demonstrate minimal decay (Skog and Nicholson 1998).

One option for treating wood product storage is to discount future release from decay to obtain a net discounted emission value (Murray 2003; Hoen and Solberg 1997). Another option is to consider the landowner's liability for carbon emissions from harvest.

Chladná (2007) presented a carbon-crediting scheme with varying levels of landowner liability for emissions, ranging from 100% (all carbon is released) to 30% (harvested wood is used in a bioenergy plant that captures and sequesters emissions). van Kooten et al. (1995) demonstrate that rotation ages are shortened as landowner liability decreases because the tax from release at harvest is lower. Long-term storage with minimal decay is analogous to a reduction in landowner liability, and therefore when wood product storage is included rotation ages are expected to shorten.

Because we include equivalent emissions in our analysis, the variable of interest changes to total equivalent carbon sequestered, TECS(t) (t C / ha). TECS(t) is calculated as the cumulative carbon sequestered, CS(t), less cumulative albedo-related equivalent emissions, A(t), as defined above. The PTE for equivalent carbon is calculated as in Equation 1 with TECS(t) substituted for CS(t). Site-specific factors such as soil albedo, frequency and duration of snowfall, vegetative cover, and intrinsic productivity, as well as management decisions such as stocking levels, species selection, and fertilization will all influence the behavior of TECS over time.

In the following analysis A(t) is assumed to follow a logistic "S-shaped" growth curve, with albedo-related equivalent emissions approaching an asymptote after canopy closure. We consider three general forms of A(t) where the initial sign of the function is negative, zero, or positive, and term these A-, A, and A+, respectively. The functional form A- reflects the findings of Bala et al. (2007) and others, who demonstrated that deforestation can have a net cooling effect, suggesting bare ground may exert a cooling influence. In such circumstances bare land, by exerting negative shortwave radiative forcing, could be said to be emitting negative equivalent carbon, or alternatively sequestering equivalent carbon. However, such cooling was observed in response to deforestation, so it remains unknown whether bare ground, ceteris paribus, actually results in equivalent sequestration. We therefore also consider other model forms for A(t).

2.6 Managing for Albedo

From the perspective of minimizing albedo-related forcing, after harvest managers may opt for alternate treatments with future stands beyond adjustment of the rotation age. One particularly compelling option is to consider changing to another merchantable species. Though the idea of planting new and different species has been proposed in the past (e.g., introducing drought resistant species where summers are expected to lengthen and rainfall decline (Krankina and Harmon 2006)), generally speaking the strategies can be regarded as mitigation of climate change symptoms. Planting new and different species, when appropriate, could also mitigate climate change causes, by sequestering carbon and exerting negative radiative forcing. In the mountainous West of the United States it may be a viable option to introduce merchantable varieties of larch (Larix), which is deciduous, for instance. Elsewhere, transitioning to merchantable hardwood species or simply emphasizing hardwood species may be appropriate. Quaking aspen (Populus tremuloides), for instance, is a ubiquitous species in the Lake States of the United States that is usually harvested using clearcuts; benefits could accrue from increased albedo in winter as well as after harvest. All other things equal, such practices would be beneficial from a climate change perspective if the discounted value of TECS, carbon sequestered from growth less equivalent carbon emissions from radiative forcing, exceeded that for the pre-existing forest type.

Another option available to landowners is to change regeneration effort. If A(t) is negative prior to canopy closure, (A- from above) it may in theory be optimal to lengthen the time until the stand reaches canopy closure. Doing so would generate a near-term benefit from the cooling influence of the bare ground acting as an equivalent sink. An additional benefit from delayed establishment is provision of early seral habitat. Conversely, if bare ground is dark enough to possibly exert a warming influence, then pursuing rapid regeneration to quickly sequester carbon may be preferable in order to offset the equivalent emissions.

Altering harvest quantity is another suggestion for reducing carbon release through forest harvest (Richards and Stokes 2004; Murray et al. 2000). Rather than pursue uneven-aged management based on single tree selection, it might be a beneficial silvicultural alternative to pursue patch cutting in even-aged management. To do so would expose bare soil that may exert negative forcing, especially in areas with high snowfall or particularly light-colored soils. Though we do not consider this latter option in this manuscript, it could be the subject of future research.

2.7 The Faustmann Model

We assume that the landowner's objective is to determine the optimal rotation age, T*, that maximizes the soil expectation value (SEV), as presented in Equation 2.

$$\max_T SEV_{tecs} = \frac{pv(T)e^{-rT} + p_c\alpha\int_0^T v'(t)e^{-rt}dt - p_c\int_0^T A'(t)e^{-rt}dt - p_c\left[\alpha v(T) - A(T)\right]e^{-rT}}{1 - e^{-rT}} \quad (2)$$

where p = net timber price ($ / m3), v(t) = timber volume (m3 / ha) at age t, r = discount rate, α = conversion factor for carbon in harvested wood volume (t C / m3), pc = carbon tax/subsidy ($ / t C), and the subscript tecs indicates this is the SEV calculated considering total equivalent carbon sequestered.. The first term in the numerator represents the value of harvested timber; the second term the incremental subsidies for increases in actual carbon stock; the third term incremental taxes on equivalent emissions; and the fourth term the tax levied when carbon is released at final harvest, adjusted for albedo-related equivalent emissions.

Integrating by parts and reducing terms yields Equation 3:

$$\max_T SEV_{tecs} = \frac{pv(T)e^{-rT} + rp_c\alpha\int_0^T v(t)e^{-rt}dt - rp_c\int_0^T A(t)e^{-rt}dt}{1 - e^{-rT}} \quad (3)$$

Taking the derivative of the SEV, setting the result equal to zero, and rearranging terms yields the first-order necessary condition (FONC) for an optimum:

$$pv'(T) + rp_c\left[\alpha v(T) - A(T)\right] = r\left[pv(T) + SEV_{tecs}\right] \quad (4)$$

Equation 4 can be interpreted as equating the marginal benefit (left side) to the marginal cost (right side) of leaving the stand to grow for another year. The marginal benefit of leaving the stand to grow is comprised of the additional value from timber growth plus interest earned on forestalled payments of taxes levied at harvest, adjusted for albedo. The marginal cost is foregone interest on the land and timber value. Value from incremental carbon growth less equivalent emissions, $p_c\left[\alpha v'(T) - A'(T)\right]$, is not included as a benefit because it would immediately be lost to taxes at harvest due to the full liability scheme.

The FONC for a tax/subsidy program that only considers actual carbon sequestered (CS) is displayed below in Equation 5. It has a similar interpretation to Equation 4, without adjustment for albedo-related emissions. With full emission liability, this FONC is identical to that presented by van Kooten et al. (1995)[2].

$$pv'(T) + rp_c\alpha v(T) = r\left[pv(T) + SEV_{cs}\right] \qquad (5)$$

Further, removing the carbon tax/subsidy pricing schemes yields the traditional timber-only Faustmann FONC, which equates the marginal value of letting the stand grow for an additional year with the interest that could be earned on the land and timber value:

$$pv'(T) = r\left[pv(T) + SEV_{baseline}\right] \qquad (6)$$

Comparing Equations 5 and 6 it can be seen that including carbon pricing provides an incentive to leave the stand uncut for a longer period by adding to the benefits the interest earned from postponed taxes. In Equation 4 the benefit of prolonging harvest is reduced by taxes levied on equivalent emissions, thereby dampening the rotation-lengthening effect. We therefore would expect rotation ages under the radiative forcing (equivalent carbon) tax/subsidy scheme to be shorter than those under a carbon-only scheme. How the rotation age determined using Equation 4 relates to the timber-only rotation age from Equation 6 depends on the relative magnitudes of $\alpha v(T)$ and $A(T)$, although with the exception of boreal areas with very slow growth rates we would expect that $\alpha v(T) > A(T)$. Generally speaking, then, we

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[2] This corresponds to a “pickling” factor of zero in the terminology of van Kooten et al. (1995).

expect the following relationship to hold: $T_{cs}^{*} \geq T_{tecs}^{*} \geq T_{baseline}^{*}$ [3]. Ultimately this is an empirical question that depends on the functional forms of v(t) and A(t).

2.8 Numerical Example

To illustrate the rotation effects described above, we consider the hypothetical case of a mixed-conifer stand located in coastal British Columbia, the volume equation and carbon/biomass ratio for which are provided by van Kooten et al. (1995). Optimal rotation ages were determined under a range of net stumpage prices, carbon prices, and functional forms for albedo-related equivalent emissions that vary with assumptions regarding the initial behavior of A(t) and impacts due to species and regeneration decisions. For simplicity we exclude thinning or other pre-harvest treatments, although some types of thinning have been reported to have positive sequestration effects (Hoover and Stout 2007). After harvest, we treat actual and equivalent carbon according to a full liability scheme, in accordance with the Faustmann equations presented in the section above.

As described in the accounting section, we assume that A(t) follows an "S-shaped" growth curve. This reflects our expectation that albedo values and albedo-related equivalent emissions change gradually as the stand establishes. The estimates for albedo-related equivalent emissions in Betts (2000) are based on the assumption that the albedo parameter values for dense conifer forest were reached within one rotation period, suggesting a gradual change in albedo, which agrees with our assumption. The time of maximum growth of A(t) was set to 15 years, which is roughly representative of the age when mixed conifers stands in coastal British Columbia reach crown closure.

In our baseline analysis we consider three functional forms for A(t), A-, A, and A+, that reflect assumptions about whether bare ground sequesters, does not affect, or emits equivalent carbon. We also consider a scenario absent any albedo-related equivalent emissions, or a "carbon only" scenario, such as that presented in Hoen and

[3] The regularity conditions for this to hold are: (a) marginal benefit is positive but increasing slower than (positive) marginal cost, or (b) the marginal benefit is positive but decreasing, and marginal costs are increasing and positive.

Solberg (1997). Betts (2000) reported that at final rotation total equivalent sequestration by coniferous plantations in British Columbia amounts to only 60% of actual carbon sequestered. Using age 60 as the rotation age[4], we therefore defined A(t) such that the ratio TECS(60) / CS(60) = 60%. For the alternate functional forms A- and A+, the ratio changes to approximately 65% and 55%, respectively.

Figure 1 displays the TECS and CS curves for the coastal forest example. Incorporating albedo-related equivalent emissions has the expected effect of reducing the total equivalent amount of sequestered carbon (TECS). Figure 1 also illustrates the effects of ground cover albedo. If bare ground is dark enough to exert a warming influence (A+) the land can initially be a source, but eventually the growth rate catches up and the stand transitions into a sink. The same is true where albedo-related equivalent emissions rates are quite high; Betts (2000) reports that in some boreal regions such as northern Canada and Russia, equivalent sequestration is negative, meaning the stand acts as a source. If to the contrary bare ground is light enough to exert a cooling influence (A-), equivalent emissions from early stand growth can offset sequestration, making the slope of TECS negative at least temporarily. Ultimately the various TECS curves converge, reflecting our expectation that despite initial differences in bare ground albedo, forest cover albedo approaches an asymptote.

For evaluating the impacts of species choice and regeneration effort we retain the basic growth equations and assume the changes are relative. Changing to a species with reduced albedo-related equivalent emissions is assumed to vertically shift downwards the A(t) function, which in turn vertically shifts upwards the TECS(t) function. Figure 2 presents this change for the neutral (A) form of A(t). Specifically we assume that the species transition increases the ratio of TECS(60) / CS(60) to 80%. Like above, this ratio increases/decreases by approximately 5% for A- and A+, respectively. Delaying regeneration effort (here we delay by 10 years) is assumed to horizontally shift both the CS(t) and A(t) functions, therefore also shifting TECS(t). Figure 3 displays this shift,

[4] Betts (2000) reported rotation ages of 40-80 years; we use the midpoint.

again for the neutral (A) form of A(t). For A- the TECS curve is immediately positive, because the bare ground acts as an equivalent sink.

2.9 Results

We compare optimal rotation ages, soil expectation values (SEV), and present tons equivalent (PTE) for three modeled management scenarios (baseline, species selection, and delay regeneration). Table 1 presents the optimal rotation age for the coastal forest example under a range of net stumpage prices, carbon prices, and functional forms for albedo-related equivalent emissions (A-, A, and A+). All optimal rotation ages were calculated use a discount rate of 5%. The first row in Table 1 assumes zero albedo-related equivalent emissions, identical to a carbon-only tax/subsidy scheme. Because we only consider relative changes to TECS for the species selection scenario, there are no carbon-related benefits to be had from changing species and so results are identical to the baseline.

In the baseline scenario, incorporating equivalent emissions from albedo has the effect of maintaining or shortening rotation ages relative to a carbon-only policy. Rotation ages decrease with increasing timber prices and increase with increasing carbon prices. This agrees with the results of van Kooten et al (1995) . Moving down rows of Table 1 (increasing albedo-related equivalent emissions from bare ground), rotation ages increase for identical timber/carbon price pairs. Entries marked as “-“ indicate a net negative soil expectation value, as the landowner will incur more costs from taxes on emissions than revenue from subsidy payments and harvest. Forest management becomes unattractive where timber prices are low and carbon prices high, especially where early albedo-related equivalent emissions are also high.

Rotation ages presented in parentheses represent local optima; in those circumstances the highest SEV occurs on 1-year “rotations” where the landowner is paid a subsidy for the equivalent sink effect of the bare ground. Additionally the landowner is paid rather than taxed at harvest by returning the land to a sink. Postponing harvest therefore postpones the subsidy, so the landowner faces a decreasing SEV. Eventually however stand growth catches up, so beyond a certain age the landowner faces rising SEV values up to the (local) optimal rotation age.

In the species scenario rotation ages are lengthened relative to the baseline scenario. This makes sense, because by reducing albedo-related equivalent emissions we are effectively moving towards the carbon-only scenario. Above we demonstrated theoretically that the optimal rotation age for CS is longer than one incorporating TECS. Even in this scenario though, it still becomes unattractive to pursue forest management under relatively low timber prices and initially high albedo-related equivalent emissions. Rotation ages under the third management scenario, delay regeneration, also demonstrate similar trends with respect to timber/carbon prices and albedo functional forms. Rotation ages as presented in Table 1 reflect the time since harvest, so the actual stand age at harvest would be 10 years younger, reflecting the 10 year delay in regeneration.

In general, as albedo-related equivalent emissions increase, optimal rotation ages approach the traditional (timber only) Faustmann rotation age from above. For the example stand, the Faustmann age is 43 years, regardless of timber price (van Kooten et al. 1995). Rotation ages under the tax/subsidy scheme most closely approach the traditional Faustmann rotation at low carbon prices and high timber prices. As stated above, however, under certain circumstances (low timber and high carbon prices) it becomes uneconomical to pursue forestry on the bare land at all This is especially true for the case of (A+), where the landowner is effectively liable for equivalent emissions stemming from bare ground as well as from forest establishment (Equation 3). In this circumstance the benefit to delaying tax on final harvest is offset by near-term payments due to albedo-related equivalent emissions.

Table 2 presents soil expectation values (SEV) for the three management scenarios, across the same range of conditions presented in Table 1. Not surprisingly SEV increases with increasing timber prices. The relationship between SEV and carbon prices depends upon scenario however. For the baseline scenario SEV decreases with increasing carbon prices, in part because near term payments are required for decreases in

TECS. As expected, SEV decreases going down rows, because landowners are increasingly liable for near term payments on equivalent emissions.

In the species selection scenario how SEV behaves with respect to carbon prices depends upon the form of A(t), though the same trend of decreasing SEV with increasing carbon prices generally holds. The two values in parenthesis, as described above, represent local optima, where the optimal solution is actually to “harvest” on a 1-year “rotation” so as to constantly receive subsidies for equivalent sequestration from bare ground. The local optima occur at a much later age where timber value growth and sequestration payments offset albedo emissions taxes. SEV here are likely higher than for lower carbon prices in part because of high near term equivalent sequestration payments.

With the delayed regeneration scenario, SEV behavior likewise varies with the form of A(t), although it generally increases with increasing carbon prices (A and A+). The highest achievable SEV occurs under this management scenario, with high timber and carbon prices, and bare ground acting initially as an equivalent sink (A-). Here the landowner receives large near term incremental subsidies and large revenues at harvest.

Table 3 provides the PTE of equivalent carbon for all three management scenarios assuming a timber price of \$25/m3 and a social discount rate of 5%. Increasing carbon prices lead to increased rotation ages (see Table 1) and therefore increased amounts of equivalent carbon sequestered; this trend agrees with results presented by Murray (2003). Our calculated carbon-only PTE values are generally lower than those in Murray (2003), which is likely due to a combination of the fact that we consider different species, employ a full liability emission scheme rather than a decay function, and the carbon/biomass ratios from van Kooten et al. (1995) may be lower than those used in Murray (2003). Negative values indicate the stand effectively acts as a source. These occur where bare ground acts as a sink, but equivalent emissions due to early stand growth result in a negative slope for TECS. The proposition that a stand can act as a source relative to bare ground with high albedo generally agrees with the results of other studies cited earlier in this paper; forests in certain locations can exert a warming rather than a cooling influence.

Table 3 highlights the importance of the albedo effect of bare ground prior to forestation. Where the ground is dark enough to initially act as a source (A+), sequestration in forests provides higher PTE benefits. Under the species scenario, this can actually result in higher PTE values than for the carbon-only scenario. This suggests that in some circumstances a carbon-only approach might actually undervalue a forests contribution to climate mitigation. Certainly this is true with tropical forests that can affect climate through other mechanisms such as evapotranspiration (Bala et al. 2007).

Table 3 also demonstrates that by incorporating the radiative forcing effects from surface albedo, which can reduce the net equivalent sequestration potential of forests, it takes longer to sequester the same discounted level of carbon as would have been accounted for under a "carbon only" scenario. At a price of $10 / t C the coastal forest stand would sequester 5.13 PTE of carbon. Now consider the species selection scenario with the neutral (A) form of A(t). To achieve roughly the same level of equivalent sequestration the carbon price would have to increase by nearly an order of magnitude. To achieve similar PTE levels with the other albedo functional forms would require even higher carbon prices, or additional government subsidies. This suggests that at the margin, other opportunities for carbon reduction relative to trees, or trees in other locations, become more attractive than they would be if albedo effects were not considered. Since the albedo effect is more pronounced in northern latitudes than in the tropics, a ton of carbon stored in the northern latitudes has less climatic impact than a ton of carbon stored in the tropics. Further, incorporating albedo-related equivalent emissions in the context of a tax/subsidy scheme appears to increase the marginal costs of sequestration.

2.10 Discussion and Conclusions

Incorporating carbon equivalent emissions from the albedo effect could provide a more complete accounting of the climatic effects of forests, with implications for climate change mitigation strategies. We demonstrated that the optimal rotation length of a managed stand determined considering TECS is reduced relative to a rotation period determined considering only CS. In general, $T^*_{cs} \geq T^*_{tecs} \geq T^*_{baseline}$. Under this radiative forcing tax/subsidy scheme, however, the degree to which rotations are extended may not be sufficient for policymakers concerned with co-benefits such as wildlife habitat and aesthetic value. Nevertheless, our results indicate that a policy aimed solely at mitigating climate change could be inefficient if it based taxes/subsidies on changes in actual carbon stock alone. If the marginal cost of sequestration increases when albedo-related equivalent emissions are included, as we suggest above, then more attention may be directed towards emissions abatement efforts, ideally resulting in innovation and increased efficiencies in abatement practices. Further, attention may be directed towards increasing sequestration in tropical regions, where in theory each ton of carbon sequestered has greater net climatic benefit.

In addition to altering optimal rotation length, incorporating albedo-related equivalent emissions into forest planning may have impacts on other forest management decisions. We addressed two important management decision variables, species choice and regeneration effort. From the point of view of maximizing PTE, changing to a merchantable species with lower equivalent emissions, such as deciduous species in snowy regions, appears to be a promising option. Delaying regeneration may also provide some climatic benefit, and in certain circumstances may lead to higher SEV for landowners.

To simplify our analysis of alternate management options we excluded some considerations that could be the subject of future research. For instance, it may not be possible in all locations to switch to another species, due to physiological or market constraints. Delaying regeneration also comes with caveats, such as increasing vegetation management costs (Sessions et al. 2004), the possibility of lower yields from natural regeneration, and green-up regulations in certain states.

Our results highlight the importance of the bare ground's albedo effect when evaluating the relative benefits of forestation. Where the bare ground acts as an equivalent sink, such as when covered in snow for most of the year, forestation does not necessarily provide climatic benefits despite the sequestration potential. This finding agrees with other research (e.g., Bala et al. 2007; Betts 2000). Alternatively, where bare ground may exert a warming influence, forestation can provide significant climate benefits.

Under certain circumstances (low timber prices and high carbon prices) forestation in the (A+) scenario proved unattractive to landowners, due to near term payments on albedo-related equivalent emissions. Clearly this is a manifestation of the particular tax/subsidy scheme employed in this paper, but is nevertheless an important point to be made. One policy question is therefore whether landowners should be liable for their land's extant climate impacts or for how their management may change said impacts. Where forestation provides clear climate benefits, compensation may be appropriate, and where it would result in undesirable climate implications, taxes may also be appropriate. Certainly our specific results reflect the particular functional forms of A(t) chosen, but the point isn't the specific values we arrived at but rather the significant differences between a carbon-only and a radiative forcing tax/subsidy paradigm.

Simplified, stand-level analysis indicates that the optimal rotation age shortens when total equivalent carbon sequestered rather than actual carbon sequestered is used as the metric. The analysis was not a thorough carbon accounting, and our results are not intended to be definitive. Continued research will improve our preliminary understanding of the albedo effect. One possible avenue is to investigate the impacts of alternate functional forms for A(t), though we anticipate that the forms would have to be radically different to significantly alter our general results. Nevertheless our analysis demonstrates the possible differences between a strategy managing for decreased radiative forcing and one managing for decreased atmospheric greenhouse gas concentrations. We hope this manuscript stimulates further research into accounting for the complete climatic impacts of forests and forest management, and how to incorporate these impacts into comprehensive climate mitigation policies.

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Figure 2.1: Total Equivalent Carbon Sequestered (TECS) for the coastal forest example, baseline scenario. The top curve represents actual carbon sequestered (CS), and the three dashed lines below it the TECS under various albedo-related equivalent emissions functional forms. The uppermost dashed curve (A-) represents the assumption that bare ground acts as a sink, the middle (A) that bare ground sequesters/emits zero equivalent carbon, and the lower curve (A+) that bare ground exerts a warming influence by emitting equivalent carbon. Ultimately the three TECS curves converge as the stand establishes forest cover and albedo stabilizes.

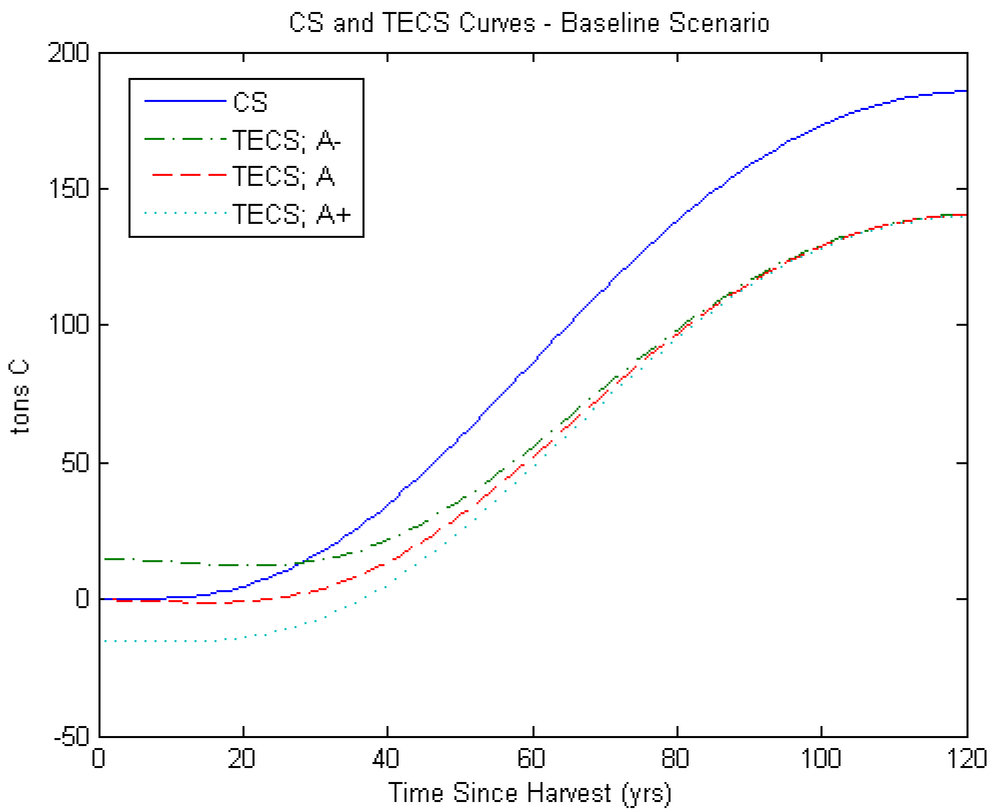

Figure 2.2: Total Equivalent Carbon Sequestered (TECS) for the coastal forest example, alternate species selection scenario. As with Figure 1, the top curve represents actual carbon sequestered (CS), and the dashed curves below TECS. The lowermost dashed curve represents the (A) curve from Figure 1, defined such that at age 60 the ratio of TECS / CS is = 0.60, in agreement with Betts (2000). The upper dashed curve is representative of a scenario wherein by selecting an alternate species (such as western larch, e.g.) the albedo-related equivalent emissions decline. In this case, the decline in equivalent emissions is such that at age 60 the ratio of TECS / CS increases to 0.80.

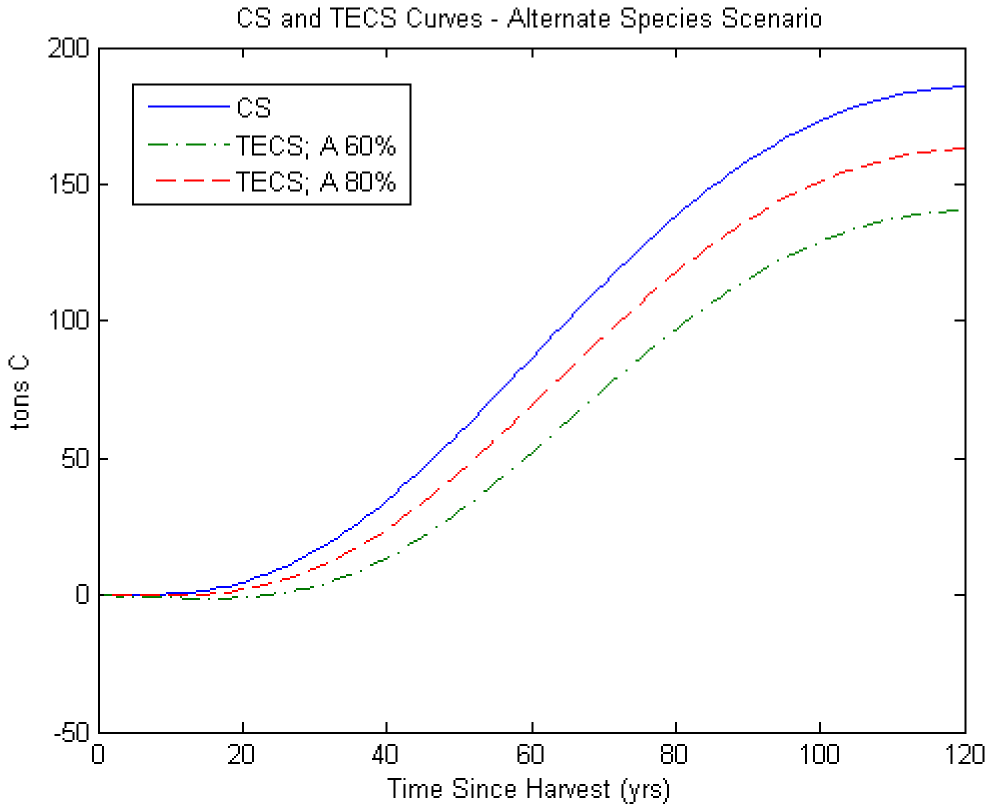

Figure 2.3: Total Equivalent Carbon Sequestered (TECS) for the coastal forest example, regeneration delay scenario. In this scenario regeneration is postponed by 10 years, resulting in a horizontal shift in TECS. The curves below in this figure were generated using the albedo function (A).

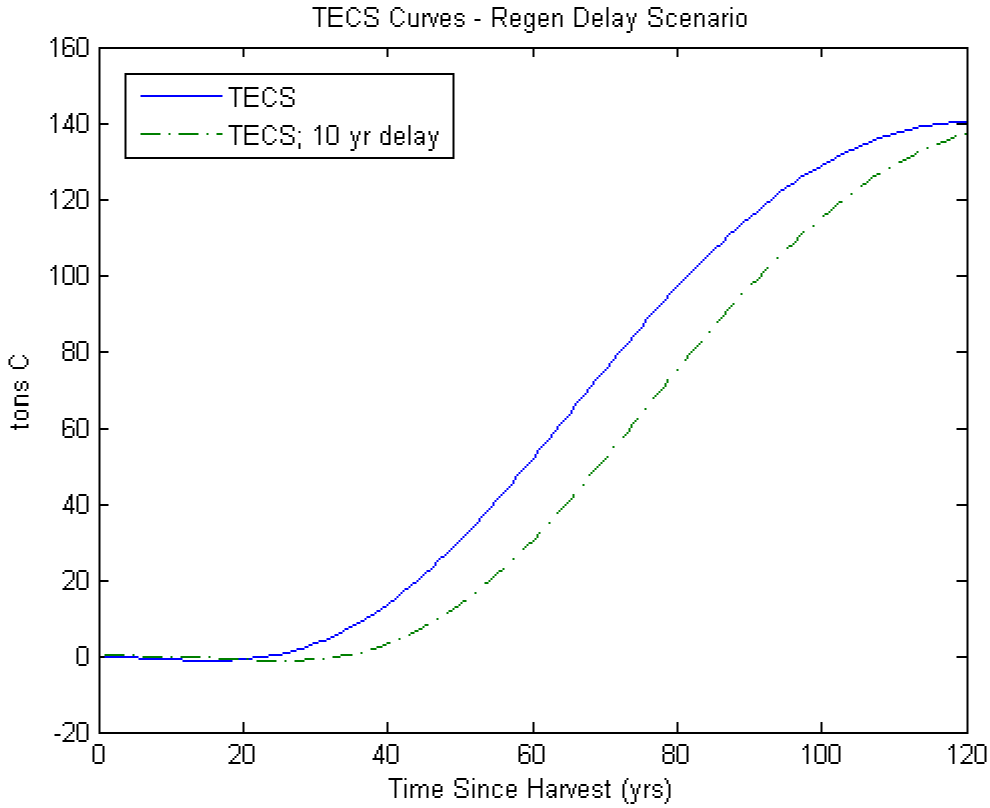

Table 2.1: Optimal rotation ages for the coastal forest example under the radiative forcing tax/subsidy scheme, across various carbon/timber prices, albedo functional forms, and management scenarios. Rotation ages presented actually represent years since harvest. Thus for the "Delay Regeneration" scenario, the stand age is actually 10 years younger than presented, reflecting the 10 year delay in regeneration. Rotation ages presented in parentheses represent local optima; see Results section for explanation.

Albedo Function / Price of Timber ($/m3)	**Management Scenario / Price of Carbon ($/metric ton)**											
	Baseline				**Species Selection**				**Delay Regeneration**			
	$10	$20	$50	$100	$10	$20	$50	$100	$10	$20	$50	$100
Carbon Only												
$15	47	51	69	148	47	51	69	148	58	63	81	170
$25	45	47	56	77	45	47	56	77	57	59	68	90
$50	44	45	49	56	44	45	49	56	56	57	60	68
A-												
$15	44	46	53	(100)	45	48	60	117	57	60	72	128
$25	44	45	47	(58)	44	46	51	66	56	58	63	78
$50	44	44	45	47	44	44	46	51	55	56	58	63
A												
$15	45	47	-	-	46	49	63	128	57	59	68	112
$25	44	45	50	-	45	46	53	71	56	57	61	72
$50	44	44	46	50	44	45	47	53	55	56	58	61
A+												
$15	46	48	-	-	46	50	-	-	56	-	-	-
$25	45	46	-	-	45	47	55	-	55	56	-	-
$50	44	45	47	-	44	45	48	55	55	55	57	-

Table 2.2: Soil Expectation Values (SEV) for the coastal forest example. Values in parentheses for the baseline scenario represent local optima, as described in the details for Table 1.

Albedo Function / Price of Timber ($/m3)	Management Scenario / Price of Carbon ($/metric ton)											
	Baseline				Species Selection				Delay Regeneration			
	$10	$20	$50	$100	$10	$20	$50	$100	$10	$20	$50	$100
Carbon Only												
$15	508	574	838	1509	508	574	838	1509	296	337	502	915
$25	806	867	1083	1586	806	867	1083	1586	469	506	641	955
$50	1556	1612	1798	2166	1556	1612	1798	2166	902	937	1053	1282
A-												
$15	434	426	402	(483)	520	593	842	1433	426	593	1116	2090
$25	738	726	693	(669)	820	891	1117	1567	599	765	1273	2166
$50	1489	1476	1440	1386	1570	1640	1854	2234	1032	1198	1697	2546
A												
$15	342	235	-	-	424	403	384	554	266	273	305	435
$25	641	533	218	-	724	699	648	663	439	445	469	536
$50	1392	1283	960	437	1474	1447	1377	1296	873	879	897	937
A+												
$15	245	44	-	-	329	214	-	-	106	-	-	-
$25	545	342	-	-	628	508	181	-	280	126	-	-
$50	1295	1090	481	-	1377	1255	901	362	714	560	98	-

Table 2.3: Present Tons Equivalent (PTE) of total equivalent carbon stock (TECS), under a variety of carbon prices and albedo-related equivalent emission function forms, for the baseline management scenario. The values presented were calculated according to Equation 1 using a social rate of time preference of 5%. Values in parentheses represent the optimal rotation age at that combination of carbon price (column) and equivalent emission functional form (row), assuming the price of timber is $25 / m3.

Management Scenario / Albedo Function	**Price of Carbon ($/metric ton)**			
	$10	$20	$50	$100
Carbon Only (Baseline)	5.13 (45)	5.62 (47)	7.77 (56)	11.69 (77)
Baseline				
A-	-2.16 (44)	-2.01 (45)	-1.71 (47)	-0.10 (58)
A	0.82 (44)	0.94 (45)	1.53 (50)	-
A+	3.88 (45)	3.96 (46)	-	-
Species Selection				
A-	-0.13 (44)	0.30 (46)	1.35 (51)	4.13 (66)
A	3.03 (45)	3.21 (46)	4.49 (53)	7.47 (71)
A+	5.98 (45)	6.27 (47)	7.57 (55)	-
Delay Regeneration				
A-	0.88 (56)	1.11 (58)	1.64 (63)	2.99 (78)
A	2.68 (56)	2.78 (57)	3.15(61)	4.13 (72)
A+	4.41 (55)	4.48 (56)	-	-

3 The Albedo Effect and Forest Offset Design

3.1 Abstract

Forestry and land-use change are often considered in the context of a cap-and-trade program, in recognition of their influence on net carbon flux and ability to mitigate climate change via increased carbon sequestration. The climatic impacts of forests are not limited to atmospheric greenhouse gas concentrations however, and a growing body of research suggests that albedo-related climatic changes stemming from land-use change may diminish or counteract the climatic benefits of sequestration. Thus a "carbon-only" accounting approach can significantly overestimate the climatic benefit of offsets, in particular afforestation. In the worst case this could result in a forest offset actually contributing to warming, and in general may reduce the environmental effectiveness of some forest offsets. Therefore a cap-and-trade system design question is whether to recognize the albedo effect into forest offset accounting frameworks. We propose that forest offset design move towards a "carbon-equivalent" accounting approach that aggregates the climatic impacts of sequestration and of surface albedo when evaluating forest offset projects. This change would result in climate mitigation efforts taking a more targeted geographic approach that emphasizes maintaining or increasing forest cover in the tropics, and that avoids afforestation in boreal and high-latitude temperate regions. Currently developing regional cap-and-trade systems in North America, however, give afforestation projects priority for offset consideration. By staying on the current path, efforts in these initiatives directed towards forest offsets may be inefficient or ineffective, and at worst counterproductive, in large parts of the area they cover. Incorporating both carbon cycle and albedo effects will lead to more informed and effective forest offset policies.

3.2 Introduction

Forestry and land-use change are often considered in the context of a cap-and-trade program, in recognition of their influence on net carbon flux and ability to mitigate climate change via increased carbon sequestration. Though the forest industry is theoretically subject to a cap just like other industry sectors, it seems more likely that the forest sector will be uncapped and eligible to generate offsets. A cap-and-trade system on carbon emissions could therefore manifestly change forest management, as landowners would see market signals to manage for additional objectives.

In the forestry context, an offset has been defined as "a planned set of activities to remove, reduce or prevent carbon dioxide emissions in the atmosphere by conserving and/or increasing on-site forest carbon stocks" (CCAR 2008). Attention therefore has been focused on identifying cost-effective methods for raising the net forest carbon flux. Though there is some debate about whether forest-based carbon sequestration is cost effective (e.g., van Kooten et al. 2004; Sohngen and Mendelsohn 2003), most generally agree that forest sequestration is competitive with other abatement measures and may play a significant role in national and global climate mitigation strategies (e.g., Tavoni et al. 2007; Lubowski et al. 2006; Boyland 2006; Richards and Stokes 2004). Pacala and Socolow (2004), for instance, include forest management in their global "wedge" strategy to stabilize atmospheric CO2 concentrations, combining reduced tropical deforestation with afforestation to achieve an annual reduction of 1 Gt C by the 50th year of implementation. Stavins and Richards (2005) estimate that a national forest-based carbon sequestration program could reduce U.S. carbon emissions by up to one-third, at costs similar to other emissions abatement programs.

There exist various mechanisms by which forests can reduce atmospheric greenhouse gas concentrations. Canadell and Raupach (2008) identify four major strategies to mitigate carbon emissions: (1) increase forested area, (2) increase the carbon density at stand and landscape levels, (3) expand the substitution of wood products for fossil-fuel products, and (4) reduce deforestation and degradation. Activities theoretically eligible to generate offsets include afforestation, reforestation, avoided deforestation, restoration, modification of management practices, establishment of short-rotation woody biomass plantations for energy production, and modified management of carbon flows in harvested wood products (Birdsey 2006).

Implementation of forest-based offsets can provide landowners with a new revenue stream for carbon sequestration, but require strict accounting to ensure that reported offsets represent actual reductions in atmospheric carbon dioxide (Cathcart and Delaney 2006). Carbon accounting generally includes five biomass pools (above-ground biomass, below-ground biomass, litter, dead wood, and soil organic carbon), though broadly accepted procedures for carbon stored in harvested wood products remains elusive (Tonn and Marland 2007). Challenges to offset design include how to establish a credible baseline scenario, ensure additionality, estimate the effects of leakage, discount for future uncertainty, account for wood product substitution effects, and allocate credit along the supply chain. Ideally an accounting framework will transparently and accurately quantify the net removal of carbon from the atmosphere attributable to a certain offset project.

However, the climatic impacts of forests are not limited to atmospheric greenhouse gas concentrations. A growing body of research suggests that location plays a significant role in determining a forest's true contribution to climate. This result can be explained in part from biogeophysical effects, in particular changes to surface albedo. Boreal forests have the greatest biogeophysical influence of all biomes on mean annual temperature (Bonan 2008). Forests are generally darker than bare or agricultural land and consequently absorb relatively more solar radiation. Due in part to this "albedo effect," boreal and high-latitude temperate forests, despite their sequestration benefits, may exert a net warming influence relative to other land-uses such as agriculture. Though this phenomenon appears to be well documented in the scientific literature (e.g., Bonan 2008; Canadell and Raupach 2008; Bala et al. 2007; Betts et al. 2007; Schaeffer et al. 2007; IPCC 2007; Gibbard et al. 2005; Marland et al. 2003; Govindasamy et al. 2001; Betts 2000; Brovkin et al. 1999), it does not appear to have made its way into policy discussions regarding forest offsets. Rather, forest offset design to date has focused almost exclusively on carbon. This makes sense within the confines of a system designed explicitly around greenhouse gas concentrations, but does not fully account for forests' climatic impacts. In the worst case this could result in a forestry offset actually contributing to warming, and in general may reduce the environmental effectiveness of forest offsets.

In this paper we explain how the failure of existing accounting frameworks to incorporate albedo and other climatic variables may lead to inefficient mitigation efforts. We begin by describing in more detail the nature of the albedo effect and how it may affect the viability of forest mitigation strategies. Then we propose the adoption of accounting practices that incorporate the albedo effect via a "carbon-equivalent" approach, and discuss its merits relative to the traditional "carbon-only" approach. We offer salient policy recommendations for offset design, and conclude by discussing the implications of adopting these recommendations.

3.3 Albedo Effect and Mitigation Strategies

The climatic impacts of carbon sequestration, surface albedo changes, and other processes can be expressed in terms of radiative forcing, defined as the net change in global irradiance (W m^{-2}) due to changes in external climate drivers (IPCC 2007). Biogeophysical feedbacks can enhance or diminish the negative climate forcing associated with increased carbon sequestration (Bonan 2008). In tropical regions, evapotranspiration can lead to cloud formation and further cooling. In boreal regions however low surface albedo exerts a positive climate forcing that may exceed the negative forcing from sequestration. This countervailing response is especially evident in snowy regions where absent forest cover the land would stay white and reflect sunlight for much of the year (Betts 2000).

The albedo of an object is the fraction of incident solar radiation it reflects. Land-use change is one variable influencing global albedo, which in turn can influence climate (IPCC 2007). Studies on historic land-use change suggest that deforestation, and associated increases in global surface albedo, led to cooling observed prior to the 20th century (Govindasamy et al. 2001; Brovkin et al. 1999). Forest management and land-use can exert negative radiative forcing by increasing carbon sequestration, but they can also exert positive forcing by reducing surface albedo. Reduction in surface albedo from forestation may therefore exert a positive forcing just like releases of carbon from wildfire or harvest.

How the albedo effect impacts offset viability varies with the project type and location. For existing forests, changing management regimes to increase carbon density is considered the most cost-effective means, in the short-term, to sequester additional carbon (Birdsey et al. 2000). Extending the rotation age in particular can significantly impact carbon storage over time (Harmon and Marks 2002), and forests managed on longer rotations store more carbon on average than forests managed on shorter rotations (Krankina and Harmon 2006). Another strategy is to manage for increased expected carbon density at the landscape level by reducing the risk of wildfire and other disturbance. This strategy can also provide near-term climatic benefits by avoiding emissions. Canadian forests, for example, are projected to be a net source of carbon emissions for the next several decades due to fire and insect outbreak (Kurz et al. 2008), and so applying treatments designed to increase forest resiliency to disturbance would likely raise the net expected carbon storage. Establishing a baseline, however, presents a challenge as disturbance is a random, unpredictable event.

The impact of the albedo effect on offset viability in this context is less clear, and depends on the degree to which management activities alter surface albedo. Treatments that do not significantly change crown cover while increasing carbon density should see no decrement. Any countervailing negative forcing due to albedo would be part of the baseline, so the increased carbon density raises the net equivalent carbon flux. Ironically, in boreal forests the consequences of *not* applying resiliency treatments may result in cooling. Randerson et al. (2006) found that increased snow exposure due to wildfire may actually result in negative annual forcing exceeding positive forcing associated with emissions.

Storage in wood products is another method to sequester carbon, which can be relatively long-lived as durable products can remain in use for many decades. Further, oxidization after use may be of little concern because in modern landfills lumber demonstrates minimal decay (Skog and Nicholson 1998). In addition to providing storage, wood products can provide substitutes for other, more energy-intensive materials (Murray et al. 2000). Despite challenges to accounting for substitution in an offset framework, it remains an environmentally viable option for mitigation and no countervailing albedo-related impacts are immediately apparent.

Offsets associated with land use change are most susceptible to the albedo effect. Afforestation can be a major source of long-term increments, but carbon gains are often not realized for many years. Because biogeophysical processes act more immediately on climate than does the carbon cycle (Bonan et al. 2008), for some boreal afforestation projects near-term warming can be expected before sequestration benefits accrue. van Minnim et al. (2008) investigated the effectiveness of sequestration in forest plantations, and stated that because of biophysical effects, plantations should not be established at high latitudes if climate mitigation is the sole objective. Schaeffer et al. (2007) compared biomass and carbon plantations in terms of their respective climate impacts via albedo and carbon sequestration. They found that the albedo effect can offset sequestration benefits and questioned the efficacy of extra-tropical carbon plantations as a mitigation strategy. Betts et al. (2007) and Gibbard et al. (2005) likewise suggested that carbon plantations outside of the tropics could be less effective than expected or even counterproductive. South (2008) suggests that foresters have not fully considered the albedo effect, and questions the efficacy of temperate afforestation efforts.

Preventing emissions associated with deforestation can provide immediate climatic benefits. The time profile of carbon flux is therefore different from that of newly planted trees, with greater near-term increments. Reducing emissions from tropical deforestation in particular could significantly contribute to overall emissions reductions (Gullison et al. 2008). Further, increased tropical forest conservation could provide synergistic biogeophysical feedback due to evapotranspiration and cloud cover, which brighten the planet. Bala et al. (2007) simulated large-scale deforestation and observed that deforestation resulted in cooling in boreal regions, essentially no change in temperate regions, and warming in tropical regions. At the global scale the net result was cooling. The albedo effect dominates the climatic response in mid to high latitudes in the northern hemisphere, whereas in tropical regions the loss of clouds due to reduced evapotranspiration increases surface incident and absorbed solar radiation which leads to cooling despite increased surface albedo.

Of course, that the net climatic impact may be cooling after deforestation does not make it on balance a desirable outcome. There may, however, be other opportunities to manage for albedo, for example through species selection (Thompson et al. 2008). Switching to plantations of deciduous species such as larch (*Larix)* may provide an albedo benefit by increasing snow exposure in winter.

3.4 Carbon-only and Carbon-equivalent Accounting

Recognizing the possible countervailing effects of albedo raises questions about the validity of certain forest offsets. As we noted above, incorporating the albedo effect can lead to different management strategies than would otherwise be pursued under a sequestration maximization objective. The "carbon-only" nature of existing accounting approaches, which ignores the albedo effect, limits their ability to accurately portray the climatic impacts of various offsets, in particular those associated with land use change. In fact, the "carbon-only" approach has been variously described as incomplete (Schaeffer et al. 2007), as giving a false impression (Betts et al. 2007), or simply as inadequate (Betts 2000).

Policymakers are therefore faced with the option to either a) retain "carbon-only" accounting approaches and accept that some offsets will not lead to 1:1 agreement between positive radiative forcing from emissions and negative forcing from sequestration, or b) move towards a more holistic approach with measurements based on radiative forcing. Marland et al. (2003) recommend climate mitigation policies focus on radiative forcing rather than greenhouse gas concentrations, and suggest that "region-specific 'discount coefficients' might be derived for a first-order attempt to adjust changes in carbon stocks according to their simultaneous effect on surface albedo and their net effect on the Earth's radiative balance," (p. 153). Thus, accounting calculations could be adjusted for albedo related climatic impacts in order to express an offset's contribution in terms of "carbon-equivalent."

Betts (2000) developed a methodology premised on the notion of radiative forcing to express the relative climate impacts of forest sequestration and albedo. In other words, radiative forcing associated with albedo changes can be also described in terms of *equivalent* carbon flux. Specifically, Betts calculated the effect on global mean radiative forcing due to local albedo changes associated with establishment of a coniferous plantation on extant cropland. He then calculated the equivalent change in terrestrial carbon stock that would result in the same global forcing via changes in atmospheric CO2 concentration. This enabled Betts to calculate the *emissions equivalent* of the shortwave forcing (EESF) due to albedo changes. The net *equivalent* carbon stock change (NESC) due to afforestation is therefore the sequestration potential (SP) less albedo-related equivalent emissions (EESF). More succinctly, NESC = SP – EESF. Figure 1 displays carbon-only (SP) and carbon-equivalent (NESC) curves for a hypothetical stand after afforestation.

The calculations of Betts (2000) suggest that boreal and temperate afforestation can result in significant quantities of equivalent emissions. Over the course of one management rotation, estimated equivalent emissions in Canada ranged from 60 to 110 t C ha^{-1}, greater than the mean sink potential of 60 t C ha^{-1}. British Columbia was an exception, where the relatively mild climate leads to less snow cover and greater growth potential. EESF values in the northern U.S. reached 80 t C ha^{-1}, and in the Rocky Mountains exceeded 100 t C ha^{-1}. The ratio NESC/SP expresses the relative efficiency of the offset in terms of equivalent sequestration potential. In the temperate U.S., net equivalent sequestration amounted to just 70-80% of actual sequestration. In British Columbia the efficiency of afforestation dropped to 60% of actual sequestration, and in the rest of Canada efficiency further dropped to -50%. In the case of negative efficiency, the net climatic result of afforestation is no different than the release of actual emissions in a quantity equal to half the sequestration potential of the offset project.

Discounting equivalent carbon flows into a present value can allow for climatic impacts of various offset projects to be expressed on a consistent basis (Stavins and Richards 2005; Richards and Stokes 2004; Murray 2003). Thompson et al. (2008) demonstrated that the present values of "carbon-equivalent" generally decrease relative to a "carbon-only" accounting approach, and can even go negative depending upon assumptions about the behavior of albedo-related equivalent emissions. As an alternative to discounting, the average storage method can be used. This accounting approach considers the average carbon stored over the course of a management rotation, projected using average carbon flows, or the mean annual increment of carbon uptake (Richards and Stokes 2004). As noted above, Betts (2000) demonstrated that albedo-related equivalent emissions over the course of a rotation can reach or exceed the mean storage potential. Clearly a "carbon-only" approach overestimates the climatic benefit of afforestation.

3.5 Forest Offset Design Should Take a Carbon-equivalent Approach

We advocate a "carbon-equivalent" approach to offset accounting, for it stays within the confines of a greenhouse gas cap-and-trade system while more fully accounting for the climatic impacts of forestry and land-use change. This approach is also premised on a more fundamental driver of climate change, radiative forcing. The carbon equivalency calculations developed by Betts (2000) could be a starting point here. Similarly, regional factors could be applied to appropriately discount carbon estimates (Marland et al. 2003). Accounting standards should be designed with flexibility so that equivalent carbon calculations can be modified as our understanding of the albedo effect improves, effectively adopting an adaptive management paradigm. Given uncertainties regarding the full climatic implications of forests, learning and evolving as policy objectives seems appropriate.

The notion of incorporating discount factors or similar adjustments into accounting practices is not new. A familiar adjustment is the conversion of other greenhouse gases (e.g., methane) into CO2-equivalent. As it relates to forest offset accounting, leakage and risk in particular merit consideration of a discounting approach. Murray et al. (2004) estimated that leakage rates associated with forest carbon sequestration projects in the U.S. could range from minimal to very high (above 90%), depending on the project type and location, and recommended leakage effects be incorporated into project/offset accounting. Sohngen and Brown (2004) considered a conservation project in Bolivia and estimated leakage rates as high as 42%, citing demand elasticity and wood decomposition rates as the most influential factors. Ruddell et al. (2007) suggested that offsets could be valued differently according to risk of carbon loss.

Though a carbon equivalent accounting approach would require more effort and would be more costly, it would promote the integrity of offsets and help ensure real additionality in terms of climatic benefits. As is required with traditional accounting methods, albedo-related equivalent carbon should only be credited or debited in response to a demonstrable change in management. Land-use change will therefore be most affected by incorporating the albedo effect into offset accounting.

Even in the absence of new accounting methodologies, the general implications of incorporating the albedo effect into offset design are clear. In boreal regions, afforestation should not be permitted as an offset type. Likewise, high-latitude temperate afforestation should be avoided, especially in snowy regions. One option is to limit the role of temperate afforestation in offset portfolios. For example, the current design question, “What percentage of overall emissions reductions can stem from offsets?” can be augmented to ask, “What percentage of offset-related emission reductions can stem from temperate afforestation?” The lower the confidence in the capacity of temperate afforestation to provide climatic benefits, the lower this threshold should be set.

Thus, offset efforts in boreal and temperate regions should be directed towards increasing on-site carbon density, reducing the risk of forest degradation, and promoting wood substitution. This recommendation conflicts with earlier research that suggested temperate afforestation is more cost-effective than changing management intensity (Sohngen and Mendelsohn 2003). Of course, including albedo-related equivalent emissions significantly changes the cost-benefit calculus for afforestation projects. Further, that there is a time lag associated with carbon gains and that albedo-related warming can be expected in the near term make extra-tropical afforestation unattractive for offsets.

In tropical regions offset efforts should be directed toward maintaining and/or increasing forest cover. Tropical forests provide synergistic climate benefits through sequestration and evapotranspiration, meaning in theory tropical afforestation projects could claim credit for equivalent carbon in excess of actual carbon flux. Of the available mitigation options, reducing emissions via prevented deforestation is considered among the least costly (Stern 2006). Gullison et al. (2008) contend that carbon payments will be necessary to promote large scale reduced deforestation efforts in the tropics, and that effective carbon market approaches will require strengthened technical and institutional capacity, consensus on robust accounting practices, and a commitment from industrialized countries to reduce emissions, thereby creating demand for carbon credits.

To recap, we have identified that tropical forests are a particularly valuable resource in climate change mitigation, and that carbon payments are a requisite for increased protection. It is a logical next step then to recommend that cap-and-trade systems allow cross-boundary offsets. That is, a polluting entity located in jurisdiction A could purchase a forest-based offset located in jurisdiction B. Though valid concerns exist regarding verification and lost opportunities for local production of co-benefits, this approach would enable the purchase of more environmentally effective offsets associated with tropical forest projects.

3.6 Implications for Emerging Cap and Trade Systems in North America

Our review of the literature identifies the following salient points: there is great potential for tropical forests to contribute to climate change mitigation, and afforestation in temperate and boreal regions should be avoided. To date these points appear only at the periphery of cap-and-trade system design, if at all. For instance, the Western Climate Initiative, which includes most states in the western U.S. as well as the Canadian provinces of British Columbia, Manitoba and Quebec, plans to give forest projects, including afforestation, priority for investigation into offset potential (Western Climate Initiative 2008). This would permit afforestation projects in boreal and high-latitude temperate regions irrespective of associated albedo-related equivalent emissions. Similarly, the Regional Greenhouse Gas Initiative, comprising the Northeast and Mid-Atlantic states, only allows afforestation offsets (Regional Greenhouse Gas Initiative 2008). Under this system there is not even the possibility of pursuing forest offsets with no countervailing albedo-related impacts, and so every forest offset implemented will likely be less effective than estimated using existing "carbon-only" accounting approaches. At the national level in the U.S., legislative efforts to create a cap-and-trade system have also been very carbon-centric. The Lieberman-Warner Climate Security Act of 2007, for instance, would allow forest offsets, such as afforestation, with demonstrable carbon stock changes (S. 2191 §2403(b)(2)(A)). Our contention is that by staying on the current path, efforts directed towards forest-based offsets may be inefficient or ineffective, and at worst actually counterproductive. Incorporating both carbon cycle and albedo effects may lead to more informed and effective forest offset policies.

Reducing atmospheric greenhouse gas concentrations, the policy objective for a cap-and-trade system, is not the sole policy objective for forest mitigation strategies. Rather, forest mitigation efforts should adopt a broader approach that incorporates both sequestration and albedo. Thus in addition to current design questions related to offset development (baseline, additionality, leakage, etc.), policymakers should also ask how to account for the albedo effect moving forward. We argue that recognition of the albedo effect necessitates a novel accounting approach. Accounting frameworks should be designed with flexibility to respond to improvements in future understanding. In the near-term, pursuing a scheme that maximizes cumulative carbon-equivalent sequestration (or that minimizes cumulative radiative forcing), is a more comprehensive and informative approach than concentrating solely on carbon sequestration.

After discounting for risk, leakage, and possible countervailing albedo effects, the net equivalent carbon gain associated with some offset projects may be significantly diminished. This may result in the abandonment or limitation of afforestation in boreal and temperate regions, with subsequent loss of opportunities for production of co-benefits (clean water, habitat, etc.). Similarly, there may be diminished economic incentive to preserve intact forests from development. As there are environmental opportunity costs associated with limiting boreal afforestation, so too there are benefits associated with the refocus of attention on maintaining or increasing tropical forest land cover. Notably, an important co-benefit is preservation of unique biodiversity not found elsewhere on the planet.

This paper emphasizes that there is no single tool to mitigate climate change, and efficient forest offsets should be one component of a multi-pronged approach for developing forest-based mitigation strategies. Incorporating the climatic impacts of land-use change associated with forest management appears to reduce the cost-effectiveness of forest offsets in some instances, making emissions abatement look relatively more appealing. In general, as concern over the actual benefit from an offset raises the bar for validation, the relative cost advantage of an offset project decreases with respect to abatement (Hall 2008).

Whether the magnitude of potential boreal and high-latitude temperate afforestation projects is significant enough to be a major concern is left for future research. It may be the case that such projects are likely to comprise only a small portion of the larger forest-based offset portfolios. Nevertheless, we demonstrated that such projects can lead to inefficiencies, and argue that potential countervailing impacts be accounted for to ensure true climatic additionality. More importantly, we re-emphasized that forest-based sequestration is just a proxy for the real ecosystem service of interest, mitigating climate change.

It is not our intent to disparage the potential of boreal and high-latitude temperate forests to contribute to climate change mitigation. Existing boreal forests comprise a significant sink, and treatments to increase carbon density or increase resilience to disturbance should provide net climatic benefits. Rather, we stress that forests' full range of climatic impacts should be accounted for in offset design. Our focus on the albedo effect in this paper is intended to be illustrative, rather than definitive, of the limitations of a “carbon-only” forest offset metric. The climatic impacts of forestry and land-use change extend beyond the carbon cycle and albedo, and these impacts should also be studied further and incorporated into mitigation strategies (Bonan 2008; Pielke, Jr. 2005; Marland et al. 2003). As the globe warms we can expect less snow cover, and so the relative importance of forests masking snow albedo will decrease (Bonan 2008). In the near-term, however, forest-based mitigation efforts should be targeted where they can be most effective.

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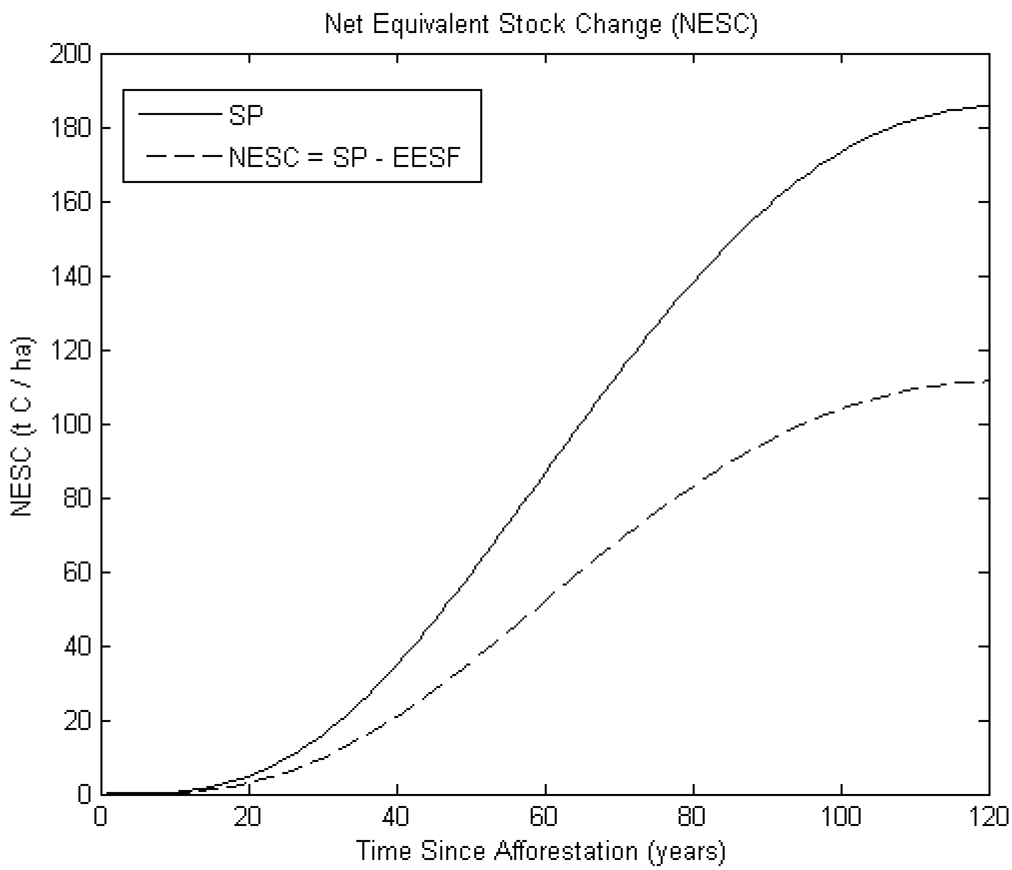
Figure 3.1: Carbon-only (SP) and carbon-equivalent (NESC) curves for a hypothetical stand after afforestation. We consider a mixed conifer stand located in coastal British Columbia, using volume and carbon/biomass equations presented by van Kooten et al. (1995). According to Betts (2000), in British Columbia net equivalent stock change after afforestation amounted to only 60% of sequestration potential. For simplicity we calculate the NESC curve assuming a constant rate of albedo-related equivalent emissions (EESF). This figure demonstrates the inaccuracy of employing a "carbon-only" accounting approach.



4 Conclusion

4.1 Concluding Remarks

This thesis explored forest-based climate mitigation strategies through the lens of the albedo effect and its possible impact on mitigation efficiency. I considered a tax/subsidy system and a cap-and-trade system, two market-based policies whose aim is to incentivize emissions reductions. In Chapter 1 I compared and contrasted these policies, briefly described forest-management strategies in the context of said policies, and introduced the albedo effect. I then identified a common thread that emerged from a review of the salient literature on climate modeling and forest management: a singular focus on carbon does not tell the entire story of forests' climatic impacts. Rather, a number of climatic variables should be accounted for, in particular surface albedo.

Changes in surface albedo in response to land-use change or other management actions can influence climate as much or more than changes in atmospheric greenhouse gas concentrations. Radiative forcing, externally imposed perturbations in the Earth's radiative energy budget, measured in W / m^2, can express the relative climatic contributions of albedo changes and carbon sequestration/release (IPCC 2007). That is, a lowering of surface albedo (e.g., transition to darker ground cover such as coniferous forest) exerts a positive forcing just like emission from wildfire or harvest does. Thus, one can think of albedo changes that exert a negative forcing as *equivalent* emissions, and one can therefore account for carbon and albedo changes with a "carbon-equivalent" approach.

In Chapters 2 and 3 I adopted a "carbon-equivalent" accounting approach, and examined the impacts on forest mitigation strategies in the context of market-based policies. For both chapters I relied on the seminal work of Betts (2000), who used the concept of radiative forcing to estimate the magnitude of equivalent emissions associated with surface albedo changes stemming from conversion of cropland to coniferous forest. Betts' (2000) calculations went as such: the net *equivalent* carbon stock change (NESC) associated with a forestation project is equal to the sequestration potential (SP) less albedo-related equivalent emissions (EESF). Thus, NESC = SP – EESF. Where management actions result in albedo-related equivalent emissions, the net climatic benefit of any activity will be diminished. In boreal regions, equivalent emissions can actually exceed the sequestration potential, meaning the net climatic result is warming. In high-latitude temperate regions, climatic benefits do not appear to go negative but are significantly reduced. In tropical regions, to the contrary, other biophysical processes such as evapotranspiration can lead to further cooling.

Chapter 2 considered a tax/subsidy system wherein landowners were paid an incremental subsidy for equivalent sequestration, and taxed for harvest and albedo-related emissions. I presented a stylized, stand-level analysis to determine the optimal (Faustmann) rotation age when landowners are taxed according to "carbon-only" and "carbon-equivalent" rubrics. In addition to harvest age, I also considered species selection and regeneration effort as management decision variables. The latter two choices are premised on the notion that it may be possible to manage for albedo in addition to managing carbon flows over time. Transitioning to deciduous species could increase snow expose in winter, exerting a cooling influence via negative forcing. Depending upon the albedo of bare ground, it may be preferable to either lengthen or shorten the time until reforestation. Where bare ground is acting as an equivalent sink (i.e., high albedo value exerts negative forcing), it might be desirable to delay regeneration in order to accrue near-term albedo-related benefits.

I demonstrated analytically that the optimal rotation length is likely shortened when albedo-related equivalent emissions are incorporated, relative to a policy based only on carbon. To verify these results I considered a hypothetical mixed-conifer stand located in British Columbia, using the growth and carbon/biomass equations published by van Kooten et al. (1995). Empirical results indicated that rotation ages do decrease relative to a "carbon only" policy, and approach the traditional (timber only) Faustmann rotation age as equivalent emission rates increase. To account for carbon and equivalent carbon I employed a discounting approach, which expresses on a consistent basis (present tons equivalent, or PTE) the climatic benefits of forest projects with variable carbon flow curves over time (Richards and Stokes 2004). Results demonstrated that it would take much longer rotation ages to sequester the same discounted level of equivalent carbon as would have been accounted for under a "carbon only" approach. Further, to achieve roughly similar levels of equivalent sequestration would require very high carbon prices, in some cases an order of magnitude (or more) higher than under a "carbon only" approach.

If the marginal cost of sequestration increases when albedo-related equivalent emissions are included, as my results suggest, then more attention may be directed towards emissions abatement efforts, ideally resulting in innovation and increased efficiencies in abatement practices. Further, attention may be directed towards increasing sequestration in tropical regions, where in theory each ton of carbon sequestered has greater net climatic benefit. From the point of view of maximizing PTE, changing to a merchantable species with lower equivalent emissions, such as deciduous species in snowy regions, appears to be a promising option. Changing regeneration practices may also provide some climatic benefit, depending upon the behavior of albedo-related emissions prior to canopy closure. In summary, the results of Chapter 2 emphasize the significant differences between a "carbon only" and a "carbon equivalent" tax/subsidy paradigm.

In Chapter 3 I built upon the results of Chapter 2, switching the focusing instead to a cap-and-trade system. At the time I author this, President-elect Barack Obama has committed to instituting a strict national cap-and-trade system with a goal of achieving 80% emissions reductions by 2050[5]. It is likely the forestry sector will not be capped but will rather be eligible to generate offsets for tradable credit, as has been implemented or proposed in emerging regional systems (e.g., Regional Greenhouse Gas Initiative, Western Climate Initiative) and in national legislation (e.g., Lieberman-Warner Climate Security Act of 2007, Bingaman-Specter Low Carbon Economy Act of 2007). Development of accounting guidelines for forest-based offsets should therefore remain a salient policy design issue in the near future.

[5] www.barackobama.com/issues/energy

Unfortunately, to date there appears to be little if any attention paid to incorporating the albedo effect into offset accounting frameworks. In Chapter 3 I therefore explored the implications of albedo-related equivalent emissions on offset viability and efficiency, and offered policy guidance for offset design moving forward. Again citing Betts (2000), I demonstrated how the climatic efficiency (defined as the ratio NESC/SP) of afforestation projects can be significantly diminished when albedo-related equivalent emissions are included. In fact, in boreal regions of Canada efficiency values went negative, indicating afforestation would exert a net warming influence. Numerous other researchers investigating the potential for forest management to mitigate climate change have echoed these results (e.g., Bonan 2008; Canadell and Raupach 2008; Bala et al. 2007; Betts et al. 2007; Schaeffer et al. 2007; IPCC 2007; Gibbard et al. 2005).

That afforestation projects in boreal and high-latitude temperate regions exert positive forcing via albedo-related equivalent emissions calls into question their viability as offsets. More broadly, the albedo effect calls into question the viability of current accounting practices that have a singular focus on carbon. Allowing high-latitude afforestation projects, as extant regional cap-and-trade programs do, could lead to inefficient or even counterproductive results. I therefore proposed that offset design move towards a "carbon equivalent" approach, wherein the climatic impacts of surface albedo would also be accounted for. This might entail the calculation of region-specific discount factors (Marland et al. 2003) to levy much like one would discount for leakage or risk. In the absence of modified accounting practices, it might simply entail the outright abandonment or limitation of afforestation in certain regions.

The implications of including surface albedo into accounting frameworks extend beyond advocating restrictions on boreal and high-latitude temperate afforestation. In particular, maintaining or increasing tropical forest cover is desirable, as other biophysical processes such as evapotranspiration provide synergistic climatic benefits. In the context of a cap-and-trade system, institutional frameworks to allow the sales of cross-boundary offsets would need to be developed. Thus emissions from a high-latitude location could be offset by a tropical afforestation project, which from a climatic benefit perspective is more desirable than a local afforestation project. Of course, lost opportunities for local production of co-benefits (clean water, habitat, etc.) and uncertainty over the rigor of extra-jurisdictional verification are disincentives to pursue cross-boundary sales.

In summary, in this thesis I reemphasized the point that the climatic impacts of forests extend beyond their capacity for sequestration, and argued that any forward-looking strategies to mitigate climate change should recognize such. In Chapter 2 I adopted a rather theoretical approach, wherein I considered a hypothetical tax/subsidy system to demonstrate that the marginal costs of sequestering equivalent carbon increase when albedo-related equivalent emissions are included. I further suggested possible strategies to manage explicitly for albedo. In Chapter 3 to the contrary I adopted a much more pragmatic approach, offering guidance for how we might best move forward with forest offset design under a cap-and-trade system. The overarching recommendations of my research are:

- Move towards a "carbon-equivalent" accounting approach that aggregates the climatic impacts of sequestration and of surface albedo when evaluating forest offset projects.
- Adopt a targeted geographic approach that emphasizes maintaining or increasing forest cover in the tropics, and that avoids afforestation in boreal and high-latitude temperate regions.
- Promote the sale of offset credits across jurisdictional boundaries, to allow offset money to flow towards relatively more valuable carbon sequestration projects in tropical locations.
- Consider management strategies that affect not only carbon flux but also surface albedo. This might entail, at a minimum, transitioning to alternative merchantable deciduous species and modifying regeneration effort. It might also include other silvicultural choices such as pursuing patch cutting over single-tree selection in uneven-aged management.

As mentioned above, currently developing regional cap-and-trade systems in North America would seem to allow afforestation projects, and to date have been focused exclusively on carbon. By staying on the current path, efforts in these initiatives directed towards forest offsets may be inefficient or ineffective, and at worst counterproductive, in large parts of the area they cover. Incorporating both carbon cycle and albedo effects will lead to more informed and effective forest offset policies.

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