Estimating Leakage From Forest Carbon Sequestration Programs

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ABSTRACT

Leakage from forest carbon sequestration—the amount of a program's direct carbon benefits undermined by carbon releases elsewhere—depends critically on demanders' ability to substitute non-targeted timber for timber targeted by the program. Analytic, econometric, and sector-level optimization models are combined to estimate leakage from different forest carbon sequestration activities. Empirical estimates for the U.S. show leakage ranges from minimal (<10 percent) to enormous (>90 percent), depending on the activity and region. Importantly, and counter to common perceptions, the proportion of a project's carbon benefits undermined by leakage is not proportionally small just because the project itself is small.

1.0 INTRODUCTION

Standing forests are a tremendous reservoir of biologically sequestered carbon. Globally, about half of all terrestrial carbon is stored in forest ecosystems (IPCC, 2000, p. 4). In the U.S. alone, the amount of carbon stored in forests is about 35 gigatons (Birdsey and Heath, 1995). Land use change (primarily deforestation) was responsible for about 20 percent of the CO_2 released to the atmosphere worldwide from 1989-1998 (IPCC, 2000, p. 5). Moreover, forests provide a wide range of benefits to society, including food, fiber, shelter, watershed services, biodiversity, recreation, and aesthetic qualities. Thus policies to prevent forest clearing have the potential to produce a wide range of climate mitigation and other social, economic, and environmental benefits. Because of the direct potential for reducing atmospheric CO_2 and the ancillary benefits referenced above, forest carbon sequestration has been widely acclaimed as an option for mitigation of greenhouse gas emissions (GHGE). Land use change and forestry (LUCF) are seen as mitigation options with potentially low opportunity costs and high ancillary benefits (see IPCC, 2000 *Special Report on Land Use, Land Use Change and Forestry*).

As policy proposals to mitigate climate change have evolved from the 1992 UN Earth Summit in Rio, it has became clear that, at least in the short-run, restrictions on the emission of GHGs would be confined to a subset of the world's economies. The culmination of these actions is the Kyoto Protocol (KP), which is directly applicable to only 38 of the world's countries, though these 38 counties constituted a majority of the world's GHGE in 1990. The partial coverage opens up the possibility that emission reductions in the countries abiding by restrictions would be offset, at least in part by an induced increase in economic activity shifting to unconstrained countries. This is the concept of *leakage* in a global, multi-sector context. Because the climatological effects of GHGE are essentially the same regardless of whether the emission comes from a constrained or unconstrained country, leakage directly undermines the actions of those abiding by the restrictions and should be taken into consideration when designing and evaluating policies.

A couple of recent developments warrant further examination of the leakage issue in climate policy. First, in early 2001, the U.S. decided not to participate in the binding agreements of the KP, thereby significantly expanding the share of world emissions generated by non-constrained countries and enhancing the potential for leakage from a KP-based global emissions control system. Another development is the increased attention paid both abroad (via the KP's Clean Development Mechanism, or CDM) and in the U.S. to "project-based" approaches to GHG mitigation. Mitigation "projects" are specific transactions between two parties. One party (the buyer) wants to emit some quantity of GHGs and chooses to "offset" part or all of these emissions by paying another party (the seller) to either cut their emissions or, in the case evaluated here, remove GHGs from the atmosphere via carbon sequestration.[1] The amount of credit the buyer

[1]The choice to purchase offsets for one's GHG emissions can either be mandatory, as in the case of an emissions cap and trade system, or a voluntary action perhaps either in anticipation of future GHG restrictions or in the interest of corporate goodwill.

receives for providing the offset should, in principle, net out any leakage caused outside the spatial and temporal boundaries of the project. One characteristic of these project transactions is that they are, by definition, location, and sector-specific. Therefore, leakage effects can spill out both within the sector directly affected by the project and across sectors. Collectively, the existence of leakage implies that programs need to be evaluated under a broad national and international accounting scheme so that leakage is estimated and the program achieves cost effective global GHGE reductions.

The specific focus of this paper is on the potential leakage from carbon sequestration projects in the forest sector, including the conversion of land from agriculture to forest (afforestation). Our objective in this paper is to provide a conceptual framework and some empirical evidence on the likely extent of leakage from these types of projects. Since leakage is market-driven and economic in origin; it requires an economic model or argument to examine its causes and to develop empirical estimates of leakage discounts. This paper reports an economic examination of the leakage effect using a mixture of a conceptual model, empirical observations, and a sectoral simulation model. In this effort, we seek to explain the following

- Interaction of market forces that cause leakage from forest sector projects,
- Key parameters that determine its magnitude, and
- Approximate extent of leakage under different scenarios

2.0 RELATED LITERATURE

While this paper focuses on leakage potential from forestry projects, it is helpful to first view the leakage problem more broadly and establish the connection between this paper and the leakage-related literature. Stavins (1997) identifies two primary channels for leakage to occur under climate mitigation policies adopted by a subset of the world's nations

1. constraints on cooperating countries shift comparative advantage in carbon-intensive goods toward non-cooperating countries, leading to a relative rise in production (and emissions) outside the cooperating coalition of parties, and
2. a unilateral policy constraining emissions may lower world demand for carbon-intensive fuels; thereby reduce the world price for such fuels. As a result, demands for such fuels (and emissions) can rise outside the coalition.

How important are these effects? Several papers have examined the potential empirical magnitude of leakage when GHG abatement actions (e.g., emissions limits, carbon taxes, or tradable permits) are applicable to only a subset of the world's countries (e.g., Oliveira-Martins et al., 1992; Felder and Rutherford, 1993; Manne and Rutherford, 1994; Jacoby et al., 1997; Smith, 1998; Bernstein et al., 1999; Barker, 1999; Babiker, 2001). These leakage estimates range from negligible (Barker, 1999) to substantial (Felder and Rutherford, 1993), but typically are in the range of 10-20 percent of targeted country emission reductions. In the case of agriculture, a modeling study Lee et al. (2000, 2002) show unilateral implementation of the KP in the U.S. leads to a decline in U.S. exports and an increase in production in the rest of the world, which is indicative of leakage.

The literature on leakage from region-specific sequestration strategies in the forest sector is not as well-developed as the multi-region and multi-sector studies referenced above. Chomitz (2002) compares the potential from leakage from forestry projects to that from energy sector projects to argue that the former are not systematically more prone to leakage than the latter (as some parties have argued they are). A study by Alig et al. (1997) uses a model of the U.S. forest and agricultural to evaluate the net effects of certain forest carbon sequestration strategies such as afforestation. While that study does not specifically estimate the size of leakage, it does find that the GHG benefits of a particular type of afforestation program are largely offset by a corresponding conversion of other forestland to agriculture. This implies large leakage potential from afforestation; however, the paper evaluates a fairly coarse policy design (forcing land from agriculture to forests) that does not provide for counter-incentives to keep existing land in forests. Therefore, it may overstate leakage effects from a more incentive compatible policy. Wear and Murray (2001) indirectly address the leakage issue by estimating the magnitude of extra-regional feedback from region-specific forest preservation policies. The feedback effects are large, though denominated in softwood lumber units not carbon. That study is featured in more detail below.

Perhaps the empirical studies most relevant to the potential extent of leakage from LUCF can be found in the economics literature on investment crowding or “slippage” from forest and agricultural conservation programs. Lee et al. (1992) examine U.S. tree-planting programs to determine whether government-subsidized tree-planting crowds out private tree-planting investment. If so, this would be indicative of leakage. Their econometric results do not strongly support a crowding-out effect. Policies such as the USDA Conservation Reserve Program (CRP) are targeted to retire land from agriculture production for soil conservation and other environmental objectives. Slippage occurs when practices on non-targeted lands generate the environmental impacts targeted by the policies. Wu (2000) finds in the case of the CRP that about 20 percent of the acres diverted from production were replaced by other acreage with 9 to 14 percent of the environmental benefits offset. Wu et al. (2001) show that such problems make cost benefit analysis of individual projects misleading and argue for more comprehensive treatment. As further evidence of offsetting responses by farmers to targeted program offerings, leakage is also found to occur with participation in U.S. crop commodity programs (Brooks et al., 1992; Hoag et al., 1993).

3.0 A MODEL FOR MEASURING LEAKAGE FROM A FOREST PRESERVATION PROJECT

To further explain leakage concepts, we first use an analytic model which focuses on a single, but important, form of forest carbon sequestration policy: forest preservation. Further into the paper, we will estimate leakage from a broader set of activities.

For the purposes of this analysis, we consider the gross and net carbon sequestration effects of forest preservation, which prohibits harvest on targeted lands establishing nature reserves, wilderness area, parks, or other forms of protected lands. As a consequence, the standing forest carbon and the soil carbon as well as all future growth in those items will remain stored for an extended period of time. In the case of forest preservation, leakage would occur to the extent that the carbon saved in the reserved forests is offset by increased harvest and accompanying carbon losses on other forest lands outside of the reserved area. This diversion of carbon losses is caused by the response of market suppliers not directly affected by harvest restriction.

3.1 Reserved and Non-Reserved Timber as Perfect Substitutes

We first examine the case where the timber produced in the reserved and unreserved areas are perfect demand substitutes. Suppose in that case we have two sources of supply in a timber market, represented by the supply functions

$$Q_R^S = Q_R^S\,(P, W_R, I_R) \tag{1}$$

$$Q_N^S = Q_N^S\,(P, W_N, I_N) \tag{2}$$

where Q_k^S (k = N, R) is the quantity of harvested wood products that could be supplied to the market from source k, P is the wood product price, W_k is a price vector of inputs used in harvesting at source k, and I_k is the fixed inventory of harvestable forest capital stock on those lands. The k subscript represents supply source where R identifies supply from sources potentially targeted by a forest preservation program, N identifies supply from outside the potentially reserved lands. Although we omit a time subscript, the supply function is conditional upon the harvestable inventory (I_k) and price signals applicable at a given point in time.

Under the assumption that the timber produced by suppliers R and N are perfect substitutes in demand, the aggregate demand function for timber is given by

$$Q^D = Q^D(P, Z) \tag{3}$$

where Z is a vector of demand shifters (e.g., income, price of substitute goods). Because the products are perfect substitutes and we assume the locations are in close proximity, suppliers R and N receive the same market price. Market equilibrium occurs when a price is determined (P*) that equates supply and demand

$$Q_N^S\,(P^*, W_N, I_N) + Q_R^S\,(P^*, W_R, I_R) = Q^D\,(P^*, Z) \tag{4}$$

For this analysis, it is helpful to think of the demand facing supply segment N as a residual demand function, that is, the difference between total market demand and the amount supplied by segment N.

$$Q_N^D (P, Z, W_R, I_R) = Q^D (P, Z) - Q_R^S (P, W_R, I_R) \quad (5)$$

Inserting (5) into the equilibrium condition (4), produces an equilibrium for segment N of

$$Q_N^S (P^*, W_N, I_N) = Q_N^D (P^*, Z, W_R, I_R) \quad (6)$$

This market setup is illustrated in Figure 1. Panel (a) depicts the total demand function, Panel (b) shows the supply function for segment R, and Panel (c) demonstrates the corresponding equilibrium for segment N. Initially, N's residual demand function, D_N reflects the difference between the total demand function D in (a) and the supply function S^R in (b). The equilibrium market price is P_0, the amount produced by supply segment N is Q_{N0}, the amount produced by supply segment R is Q_{R0}, and the total amount produced and consumed is $Q_0 = Q_{N0} + Q_{R0}$.

Suppose a policy goes into effect that compensates landowners to forego timber harvests on all of the forests comprising supply segment R. In essence, supply segment R leaves the market, $Q_R = Q_R (P^*, W_R, I_R) = 0$, and all demand must be met by segment N. This is depicted in Figure 1 by an outward shift in N's demand function from the initial residual demand function D_N to the total market demand function $D_N' = D$. At the baseline price of P_0, the magnitude of the outward shift is exactly equal to the amount that would be produced by supply segment R if the preservation policy were not in effect [$Q_{R0} = Q_R^S (P_0, W_R, I_R)$]. The demand shift reflects the fact that the policy causes all of R's demand to gravitate directly to N.

When the outward shift in N's demand function occurs, this disrupts the initial price/quantity equilibrium (P_0, Q_{N0}, Q_{R0}) and creates excess demand relative to supply. In order for the market to clear again, the price will rise to induce more supply into the market from additional harvest on the non-reserved lands and will simultaneously reduce the quantity demanded. This will continue until the new market equilibrium is reached at (P_1, Q_{N1}). The market-clearing process causes N's harvest quantity to expand from the initial value of Q_{N0} to the new equilibrium quantity of Q_{N1}. The release of sequestered forest carbon caused by this price-induced supply response is the leakage effect. The net society-wide GHG effect is the additional carbon that is sequestered on the reserved forest (R) less the carbon releases from the harvests induced on the non-reserved forests, N.

The magnitude of N's demand shift can be measured by a parameter equal to the ratio of the baseline supply quantity from the reserved forest to the baseline supply quantity from the non-reserved forest. Lets call this the "preservation" parameter, $\phi = Q_{R0}/Q_{N0}$. In Figure 1, this is the proportional increase in demand quantity from Q_{N0} to Q_0, the horizontal distance of the outward shift of the demand function. Appendix A demonstrates how the ϕ parameter can be incorporated into a market model combined with timber supply and demand elasticities and data on carbon emitted per unit harvested to derive a mathematical expression for the leakage effect. That expression is

$$L = \frac{100 * e * C_N}{[e - E^*(1 + \phi)]\ C_R} \tag{7}$$

where e is the supply price elasticity, which is assumed the same for both forest groups, E is the price elasticity of demand, C_N is the carbon sequestration reduction per unit of harvest from the non-reserved forest and C_R is the carbon sequestration per unit of (foregone) harvest gained by preserving the reserved forest. L provides an estimate of the leakage effect in percentage terms and equals the amount of carbon released through diverted harvests divided by the amount of carbon saved on the preserved forest times 100.

Numerical Simulation Results: Perfect Substitutes Model

Table 1 presents estimates for L derived from the model in (7) under different parameter values for the elasticities (e, E), relative magnitude of the foregone harvests from preserved lands (ϕ), and the ratio of carbon emissions on non-preserved forests to preserved forests (C_N/C_R).

Case 1 represents a situation where the reserved portion of the total forest inventory is non-trivial (10 percent), supply and demand are moderately responsive to price (elasticities of one) and the emission factor ratio is one (i.e., the carbon content per unit of preserved forest inventory is identical to the carbon content per unit of the harvests induced elsewhere). In this case the leakage factor is nearly 50 percent.

The leakage effect shrinks when supply is more inelastic, all else equal (Case 2). Alternatively, leakage increases when demand is more inelastic (Case 3), because demanders will be strongly inclined to obtain the harvested material somewhere. Conversely, when demand is very elastic, (Case 4) leakage diminishes; in the extreme case of infinite or perfect elasticity (Case 5), there is no leakage. Case 6 deals with a very small project in a large economy where the share of production is small but leakage is still about 50 percent.

The final example in Table 1 (Case 7) considers the effects when the per unit carbon losses from harvest of non-reserved forests are less than the per unit carbon savings on the reserved forest. This might occur, for instance, when preservation occurs on old-growth forests with high carbon content per unit of timber output (e.g., particularly C-saturated soils) and the offsetting activities occur on forest plantations with lower carbon density. When this asymmetry occurs, this diminishes the leakage effect proportionately. Conversely, if the reserved forests are less C-dense than the non-reserved forests, leakage effects would rise.

3.2 Leakage When Timber Products are Imperfect Substitutes

Timber from reserved areas will not always be easily replaced. Forest preservation is often targeted in areas that have unique ecological characteristics, thereby enhancing the preservation benefits. Consequently, the preserved forest may contain unique species or qualities of timber that do not have close substitutes outside the preserved site. This may limit the degree to which demanders seek harvests elsewhere and thereby limit leakage from the policy. That suggests the homogeneous commodity assumptions above could introduce upward leakage estimate biases as it tends to maximize the extent to which the market would simply relocate the harvests. We therefore extend the perfect substitution case here to include the case of differentiated products.

The leakage effects of imperfect substitution can be illustrated by reference back to Figure 1, specifically the supply and residual demand functions for segment N. Let N's residual demand function (D_N) shift caused by the preservation policy be expressed

$$\Omega_{RDN} = +\gamma Q_{R0} \tag{8}$$

where Ω_{DN} is the magnitude (the horizontal distance) of the outward shift in D_N caused by the removal of R's supply from the market, holding all other demand factors constant. The substitution parameter, γ, captures the extent to which the residual demand for product N shifts out in response to the elimination of product R. When $\gamma = 1$, there is a 1:1 relationship between the amount of product R withdrawn from the market and the increase in the demand for product N. In other words, R and N are perfect substitutes. When $\gamma = 0$, the products are in completely separate markets and there is no substitution at all between them and no shift in N's demand function.[2]

Figure 1 (perfect substitutability between R and N timber) reflects the case of $\gamma = 1$. If $\gamma = 0.5$, the products are moderate substitutes, D_N would only shift out half as far as in the perfect substitutes case of Figure 1. Consequently, the harvest response from the N sector to R's withdrawal of harvests from the market—and the corresponding leakage—is muted. Equation (5) can be modified to capture these substitution effects (see Appendix A).

$$L' = \frac{100 * e * \gamma * C_N}{[e - E * (1 + \gamma * \phi)]\, C_R} \tag{9}$$

Numerical Results: Imperfect Substitutes Model

We can again demonstrate the results by plugging numbers into (9). If we go to the case of $e = 1$, $E = -1$, $\phi = 0.1$, $C_N/C_R = 1$, and set the γ parameter to 0.8 (strong, but not perfect, substitutes), we get a lower leakage rate, $L' = 0.385$. If we set $\gamma = 0.2$ (weak substitutes), we get $L' = 0.099$. And of course if there are no substitution possibilities, $\gamma = 0$, leakage is zero.

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[2] γ could, in principle take on a negative value, implying the products are complements rather than substitutes, but that possibility is not central to the leakage story and is not addressed further in this paper.

3.3 Will Reserves in Small Countries Avoid Leakage?

It has been argued that leakage is likely minimal if establishing a reserve in a small country that exports a homogeneous timber commodity into the large world market (see, e.g., Chomitz, 2002). However we offer a different view. Being small players on the world market, these countries do face a highly elastic demand curve for timber. In the extreme, they are pure price takers facing an infinitely elastic demand. Thus the situation described by Case 5 in Table 1 might seem to pertain, suggesting that a forest preservation project in this country would have no leakage effects. We believe the no leakage implication is correct, but only within the country. No leakage occurs within country because the export price determines the amount of timber supplied by that country and that price will not affected by the preservation project and thus will not affect harvest incentives anywhere else within the country.

However, we believe the correct way to view the small country situation appears in Case 6. The overall world market has a modest (not infinite) demand elasticity, but the small country market share is very small, thereby leaving *that country* with a highly elastic residual demand on the world market. Leakage does occur in this situation, but the harvests shift to outside the country instead of within. To see this, consider the components of a country's export demand function. The export demand faced by country s after considering supply and demand actions in the rest of the world (Q^{DX}_{s}) can be expressed as a function of total world demand (Q^{D}_{W}) and the amount supplied by the rest of the world (Q^{S}_{ROW}), both of which are a function of the world (export) price (P).[3]

$$Q^{DX}_{S} = Q^{D}_{W}(P) - Q^{S}_{ROW}(P) \tag{10}$$

It can readily be shown (see Appendix B) that the demand elasticity facing small country s (E^{X}_{s}) is a function of the world demand elasticity (E_W), the supply elasticity from the rest of the world (e_{row}), the share of country i exports in total world consumption (H^{X}_{s}) and the ratio of country i's exports to total rest-of-world production (H^{W}_{S})

$$E^{X}_{S} = E_W\,(1/\,H^{X}_{S}) - e_{row}(1\,/\,H^{W}_{S}) \tag{11}$$

This shows country s export demand elasticity is inversely proportional to its share of the world market. When this share is very small, the demand elasticity the country faces is very large, all else equal. Under a world demand elasticity of –1.0, a world supply elasticity of +1.0 and country s export share of the world market is about 1 percent the relevant export demand elasticity is –200, which for all practical purposes is perfectly elastic. Again, using this value in the leakage equation would yield a very low estimate of leakage within small country S. But the reason that the export demand elasticity is so elastic is that there is an ample amount of supply elsewhere in the world to offset any reduction in Country S exports without a noticeable effect on world price. In other words, an elastic demand facing Country S suggests there are ample

[3] Transportation costs are ignored here without loss of generality.

extramural leakage opportunities when Country S reduces production in the name of sequestration.

In order to evaluate the magnitude of leakage in such cases, one would either need: (1) an integrated model of global forest products trade and carbon accounting or (2) to treat the supply and demand equations in our leakage calculation as if they are global timber supply and demand equations. The former is outside the scope of this paper, so we proxy for these global effects by treating the isolated forest preservation project as if it caused a very small (0.1 percent) increase in the residual demand function for unreserved forests. This is Case 6 in Table 1. It is important to note that the leakage effect is still substantial being one-half the size of that with the larger demand elasticity (Case 1). This suggests that relatively small projects in small countries do *not* systematically have smaller proportional net leakage effects.

The point just made about small countries and leakage is relevant only to the issue of scale effects. In other words, leakage is not proportionally smaller just because projects are small. However, if the timber produced by a small country is sufficiently unique, the lack of substitutability with the non-reserved timber, ($\gamma<1$) as referenced above, may apply. If a small timber-exporting country such as Costa Rica or Bolivia produces highly specialized timber, its withdrawal from the market may not be entirely offset by an increase in demand elsewhere. However, any corresponding effects in mitigating leakage is due to the product differentiation factor (γ), not to the scale factor (ϕ).

But one must be careful not to confuse the limited substitutability of a species with the limited substitutability of a species from a particular site. For example, mahogany is a unique and highly valued tropical hardwood that may be considered to have few close substitutes. However, mahogany, as rare as it may be, is not confined to just a few sites. So, for instance, if mahogany harvests are curtailed at a particular site in Bolivia, demanders may still seek mahogany at unrestricted sites in Bolivia, Brazil, and elsewhere in the tropics. In fact, the notion that mahogany as a species has relatively few close substitutes tends to make the aggregate demand for mahogany less elastic to price (see Merry and Carter, 2001 for econometric estimates of Bolivian export mahogany demand). As shown in Table 1, more inelastic demand increases the extent to which demanders continue to seek harvests elsewhere even at higher prices, thereby enhancing leakage. Thus, it is not entirely clear that timber heterogeneity will necessarily lessen leakage.

3.4 Caveats with the Analytical Model

The above analytics focus on the short-run leakage effects of forest preservation caused by harvests diverted to unreserved forests but does not address the long-run effect of management responses. As shown here, removing forest inventory from the harvest base raises timber prices. In addition to inducing harvests elsewhere, the rise in prices will induce management responses such as afforestation and increased forest management intensity. Although these responses are driven by timber market incentives, they will typically enhance carbon storage as well. Thus there may be indirect—and positive—induced effects on carbon of the preservation policies that are not considered in the analysis thus far. The broader scope of activities will be examined in Section 4 below.

Up to this point, the emphasis of the forest preservation leakage story has been on feedback from the timber market. But people clear forests for a wide range of purposes, some of which have little to do with timber returns. A prominent incentive for land-clearing, especially in developing countries, is agricultural expansion. If a forest that is reserved that would otherwise be converted for agriculture, the operative issue for evaluating leakage is which markets are affected. The demand for land from shifting cultivators will presumably still exist. Thus at least some of the deforestation seems likely to shift from protected to unprotected lands, unless specific measures are taken to reduce the land intensity of agricultural practices. Consequently, leakage potential under these circumstances would seemingly be high. Thus, one must look at feedback from the land market to get a better handle on leakage. We expand the analysis below to look at land market interactions in the context of well-developed land markets in the U.S. But we recognize that the assessment is more complex in settings where land market institutions are not as well-developed.

3.5 Do the Leakage Examples Above Hold Up Empirically? An Examination of Forest Preservation in the U.S. Pacific Northwest

To provide empirical validity to the implications drawn from the above model, consider an actual preservation case. In particular, consider the effects of U.S. federal restrictions on the sale and harvest of old growth timber that were implemented in the 1990s creating a large forest reserve. During a 10-year this time period, the volume of Pacific Northwest (PNW) timber harvested from public lands was reduced by about 85 percent and appears today likely to stay at that reduced level. Such a reduction, which was a result largely of endangered species and other ecological concerns, could also have been done in the name of forest preservation and carbon sequestration.

Wear and Murray (WM, 2001) investigated this case to see what happened to the production of timber in other regions which certainly bears on leakage. They estimated an econometric model of the U.S. softwood lumber market, which aggregated sources of supply into that from the PNW, the U.S. South, and Canada. In turn they used the model to simulate the effect of the reduction in timber sales from federal forests in the PNW. Simulated variables included the U.S. lumber price and the distribution of output and timber harvests across North American regions.

A summary table of WM's results under the assumption that $C_N=C_R$ or with leakage expressed solely in terms of production (i.e., we express leakage in terms of timber produced, rather than carbon since Wear and Murray (WM) did not delve into carbon matters) is presented in Table 2. The average annual federal timber harvest reduction in the U.S. West for the period 1990–1995 was approximately 2.1 billion board feet. However, WM estimate that private harvests in the

West rose by 895 million board feet in response. Thus, just within the region, the leakage factor results indicate about 43 percent of the reduction leaked away being replaced by other regionally induced harvests. The leakage effect increases when we expand the effects in the U.S. South and Canada. WM estimate an additional 300 million board foot harvest response raising the continental U.S. leakage estimate to 58 percent. Finally, WM estimate a 550 million board foot response in Canada resulting in a North American continental scale leakage estimate of 84 percent.[4]

4.0 A BROADER EXAMINATION OF LEAKAGE—FASOM SIMULATION

Leakage is a substantially broader concept than has been examined above. Induced afforestation, another prominent carbon sequestration policy option, may cause changes in commodity and land markets that cause countervailing reductions in management intensity on existing forests or land use change from forest to other uses such as agriculture. Leakage may also occur intertemporally with current programs causing a time stream of near term carbon sequestration followed by later releases. We were unable to investigate such intertemporal phenomena with an analytically tractable theoretical model and thus turned to an empirically based simulation model. In particular, we used the FASOM forest and agricultural sector model (Adams et al., 1996) to investigate empirical leakage consequences.

FASOM is an intertemporal, price-endogenous, spatial equilibrium model simulating temporal activities in and land transfers between the agricultural and forestry sectors. FASOM uses a mathematical programming approach and maximizes the present value of aggregate consumers' and producers' surplus in both sectors subject to resource constraints. The results from FASOM simulate prices, productions, management, and consumption. In FASOM, the United States is divided into 11 regions and includes 48 primary and 45 secondary commodities and 3 forest products. The timber growth depends upon land class, owner type, species, site class, and management intensities while the agricultural sector activities are based on the agricultural sector model (Chang et al., 1992).

The carbon sector in FASOM accounts for terrestrial carbon in 1) forest ecosystems on existing forest stands, 2) regenerated and afforested stands, 3) non-commercial carbon pools after harvest, 4) harvested timber products, and 5) agricultural lands. A new version of FASOM—FASOMGHG—is used (Lee, 2002) which expands the accounting to include 1) soil sequestration in agriculture sector as influenced by tillage practice or and land use shifts, livestock management and a number of other carbon pools adapting the accounting from the ASMGHG agricultural sector model (Schneider, 2000; McCarl and Schneider, 2001).

The modified version of FASOM was solved repeatedly by adding additional policy constraints in each case listed below.

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[4]If we compare these results to the formula above (equation 7) using parameters derived from the WM model ($e = +0.46$ – a weighted average of all 4 supply regions, $E = -0.06$, $\phi = 0.045$) we get a predicted leakage level of 87 percent.

1. **Forest setasides:** Establishment of a forest reserve that removes specific acreage from the private harvest base. The scenario targets acres that would otherwise be harvested in the model's base scenario. We examine, separately, the Pacific Northwest and U.S. South.
2. **Avoided deforestation:** Forestland that was projected to be converted to agriculture under baseline conditions is kept in forest forever and treated one of two ways: (1) preserved without harvest; (2) allowed to continue on a perpetual harvest-reforestation cycle. Simulations are run separately for each region.
3. **Afforestation:** A 10-million acre afforestation program applied, in separate scenarios, to different regions.
4. **Afforestation/avoided deforestation**: A dual national policy of payment incentives (credits) for carbon sequestered on afforested acres and charges for carbon lost on deforested acres. This scenario is motivated by the afforestation/reforestation/deforestation (ARD) provisions of Article 3.3 of the Kyoto Protocol.

Carbon payments were evaluated at prices ranging from $5 to $500 per ton of carbon.

FASOM generates a stream of outputs from the forest and agricultural sector for each decade from 2000 to 2070. Simulated variables include carbon stocks and flows, timber harvest volumes, forest management intensity, harvest rotation lengths, international trade volume, program costs, and social welfare measures (producer and consumer surplus). Given the emphasis on leakage estimation here, we focus our discussion here on carbon quantity effects. We modify the leakage measures from the analytical model above to account for the intertemporal dimension of carbon flows.

$$L^T = [(PV_P - PV_T)/PV_T]*100 \tag{12}$$

PV_P is the time-discounted present value of carbon sequestration increment on lands targeted by the policy. PV_T is the corresponding discounted value of carbon increments on all lands (targeted and non-targeted). The present value measures are calculated in standard fashion

$$PV_j = \sum_{t=1}^{T} \frac{c_{jt}}{(1 + r)^t} \tag{13}$$

The c_{jt} variable represents carbon increment on land area j (P or T) at time t. We use a discount rate (r) of 4 percent in these simulations. The results for each case are presented below

4.1 Forest Setaside Program Results

We consider forest preservation projects in two regions of the U.S.: old-growth forests of the west side of the Pacific Northwest (PNWW) and harvestable mature forests in the South-central (SC) region. The simulation is executed by identifying approximately 100,000 acres of old-growth that would have been harvested in the PNWW under FASOM's baseline run and permanently setting aside these lands from harvesting in a FASOM policy run. Likewise, we set aside roughly 660,000 acres in the SC region fitting these characteristics.

The two regional scenarios are run independently and generate leakage estimates (L^T) of 16.2 percent for the PNWW and 68.3 percent for the SC. The difference in these two values can be explained in part by the relative carbon densities of forests in the PNWW and SC. When an old-growth forest is set aside in the PNWW, this diverts harvests to other regions, such as the SC, where the carbon losses from harvest will not be as large as the carbon savings from the setaside. Conversely, protecting a relatively less carbon-dense forest in the South diverts harvests to the more carbon rich PNWW, potentially causing large leakage effects.

4.2 Avoided Deforestation Results

The avoided deforestation scenario differs from the setaside scenario just analyzed. This policy is targeted specifically on lands that would otherwise convert to agriculture in the baseline, whereas the setaside policy simply removes from the potential harvest base mature forests that would otherwise be slated for a perpetual harvest-reforest regime. The results are presented in Table 3 for candidate projects in several regions and for the two variations of allowed activity on the targeted land.

The lowest leakage is found in the Pacific Northwest eastside (PNWE), again suggesting that actions that protect these forests may divert harvesting and deforestation to regions where the carbon losses are not as severe. Lake States leakage is quite high, over 90 percent under the no harvest scenario. This suggests that protecting specific forest tracts from agricultural conversion in this region might simply divert forest clearing to other areas within and outside the region and thereby do little to generate net carbon gains.

Allowing harvests on the land that is saved from deforestation reduces leakage, all else equal. To clarify, allowing harvests on this land does not necessarily enhance the amount of carbon that is sequestered. Rather, it means that the net amount of carbon that is sequestered, measured, and verified on the targeted lands should receive less of a deduction in credits for the leakage caused outside the targeted lands. Because harvesting is allowed on these lands, it does not shift as much harvesting outside the project area.

Note that slightly negative leakage is found in the Corn Belt/harvesting allowed example. Negative leakage implies that the activities on targeted lands generate positive carbon spillovers on non-targeted lands. This might occur, for instance, if forest preservation pushes up timber prices enough to induce management investments elsewhere that more than make up for displaced harvests. However, the one negative leakage value found here is quite small (–4.4 percent) and thus perhaps not too much should be inferred about the presence of positive spillover effects from this single estimate.

4.3 Afforestation Program Results

Table 4 presents the results of fairly large (10 million acre) region-specific program to move land from agriculture to forests. We run these scenarios separately (e.g., only one program is in effect for each run of FASOM) for regions that have some history of large-scale movement of land between these two uses, thereby focusing on the eastern U.S. leakage estimates range from just under 20 percent in the Lake States to just over 40 percent in the two southern regions. It is not surprising to find larger leakage effects in the South, as that is the region of the U.S. where afforestation, reforestation, and forest management are the most intense. Thus, we should expect that targeted afforestation projects there are more likely to displace activity that would otherwise occur on non-targeted lands.

4.4 Afforestation-Avoided Deforestation Results

We simulate a national policy that pays carbon credits for land that moves from agriculture to forests and charges carbon debits for land that is deforested, much like one that might have sprung from implementation of Article 3.3 of the KP. Land that does not change use is unaffected by the policy. It is the corresponding management responses on those lands, and the carbon consequences thereof, that constitutes leakage. For instance, more land in forests could depress timber prices, thereby reducing the incentive for forest management—and, jointly, carbon management—on non-targeted lands.

Figure 2 presents the leakage estimates for this scenario under the wide range of carbon prices considered. First note the magnitude. Leakage estimates range from 7 to 17 percent. These estimates are lower than those found with the pure afforestation scenario above. The primary reason for this is that deforestation is penalized in this scenario and thereby discourages some of the offsetting land movements that might occur in a program that focuses entirely on the one-way movement of land from agriculture to forest. Second, note the pattern of the relationship between the carbon price and the leakage effect. At higher carbon prices, the leakage effect declines.[5] Because the scale of the targeted program is larger at higher prices—i.e., there is greater participation when the incentives are higher—this provide some evidence that leakage effects are proportionately higher the smaller the project. This pattern of estimates runs counter to previously cited arguments that small project are likely to generate less leakage, all else equal.

5.0 CONCLUSIONS

This paper uses economic principles, data, and methods to frame the leakage issue in the context of forest-sector climate mitigation projects. We find that, under some circumstances, leakage from geographically targeted mitigation projects can be sizeable and in other cases it is not. Moreover, in contrast to common perceptions, just because a project is small it does not mean

[5]Note that this is a percentage decline in the leakage effect (leaked carbon relative to targeted carbon), not an absolute decline in leaked carbon.

that leakage outside of the project boundaries can be ignored. A clear implication of this is that policy designers and market makers should adequately account for leakage effects when enabling exchanges of GHG offsets.

The empirical results presented here are primarily applicable to the U.S., where land, agricultural, and timber markets are well-developed. Results could certainly differ elsewhere. Well-functioning markets tend to expand the geographic boundary of market exchanges and thereby expand the area in which leakage may occur. Thus, in that sense, our estimates may be seen as upper-end values. However, it should be noted that the economic model used to generate most of our estimates operates at the national level and focuses on two sectors of the economy. Since international and inter-sectoral leakages are also possible, the absence of those effects in our model may lead to an understatement of leakage. Clearly better integration of sector-level models with broader computable general equilibrium models operating on an international scale is needed.

While the emphasis here has been on estimating the size of leakage effects from mitigation projects in forestry, leakage effects are not just endemic to this sector. Similar adjustments should also be made in accounting for projects in the energy sector and other parts of the economy using empirically based estimates generated by economic models.

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Table 1. Leakage Calculations for Forest Preservation Example with Perfect Subsitutes for Reserved Timber (γ = 1)

Case	(e) Supply Elasticity	(E) Demand Elasticity	(ϕ) Relative Size of Reserved Acreage	(C_N/C_P) Emission Factor Ratio	(L)[a] Leakage Effect (%)
1	1	–1	0.1	1	47.6
2	0.3	–1	0.1	1	21.4
3	1	–0.1	0.1	1	90.1
4	1	–5	0.1	1	15.4
5	1	–∞	0.1	1	0.0
6	1	–1	0.001	1	50.0
7	1	–1	0.1	0.5	23.8

[a]From equation (7)

$$L = \frac{100 * e * C_N}{[e - E*(1 + \phi)]\ C_R}$$

Table 2. Estimated Harvest Leakage Effects from Federal Timber Restrictions in the U.S. Pacific Northwest (from Wear and Murray 2001)

Public Harvest Timber Reductions	Million Board Feet	
West coast	1,200.4	
Inland west	866.8	
Total west	2,067.2	
Induced Harvests Elsewhere		**Percent Leakage[b]**
Western private lands	894.6	43.3%
South	298.9	
U.S. total	1,193.5	57.7%
Canada	550.4	
North America total	1,744.0	84.4%

[a]All quantities are in million board feet, timber scale (1990-1995 annual average)

[b]Leakage = Induced harvest in area i divided by Total West public harvest reduction.

Table 3. Avoided Deforestation Leakage Results (All Quantities Are Percentages)

Region	No Harvesting Allowed	Harvesting Allowed
Pacific Northwest—east side	8.9	7.9
Northeast	43.1	41.4
Lake states	92.2	73.4
Corn belt	31.5	–4.4
South-central	28.8	21.3

Table 4. Afforestation Program Leakage Estimates by Region (All Quantities Are Percentages)

Region	Leakage Estimate (%)
Northeast	23.2
Lake states	18.3
Corn belt	30.2
Southeast	40.6
South-central	42.5

Figure 1. How Creating a Forest Reserve Can Shift Timber Harvests to Non-Reserved Forests

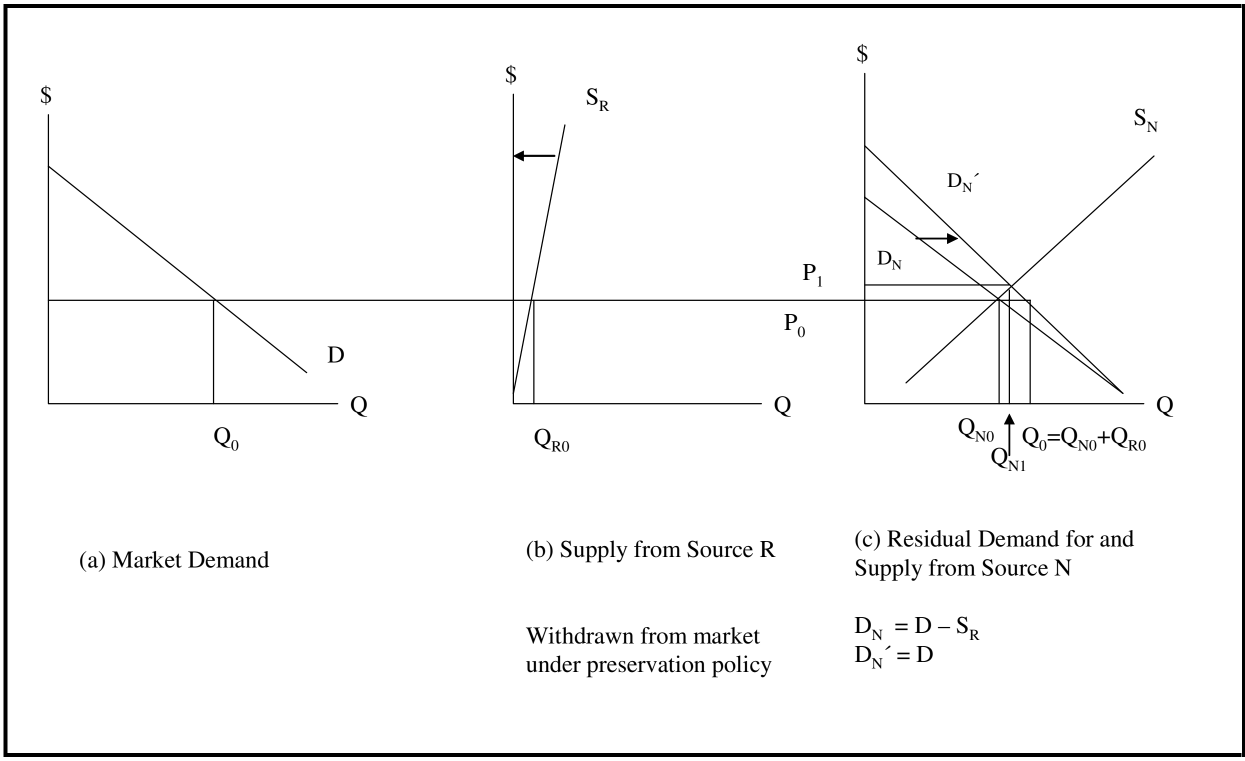
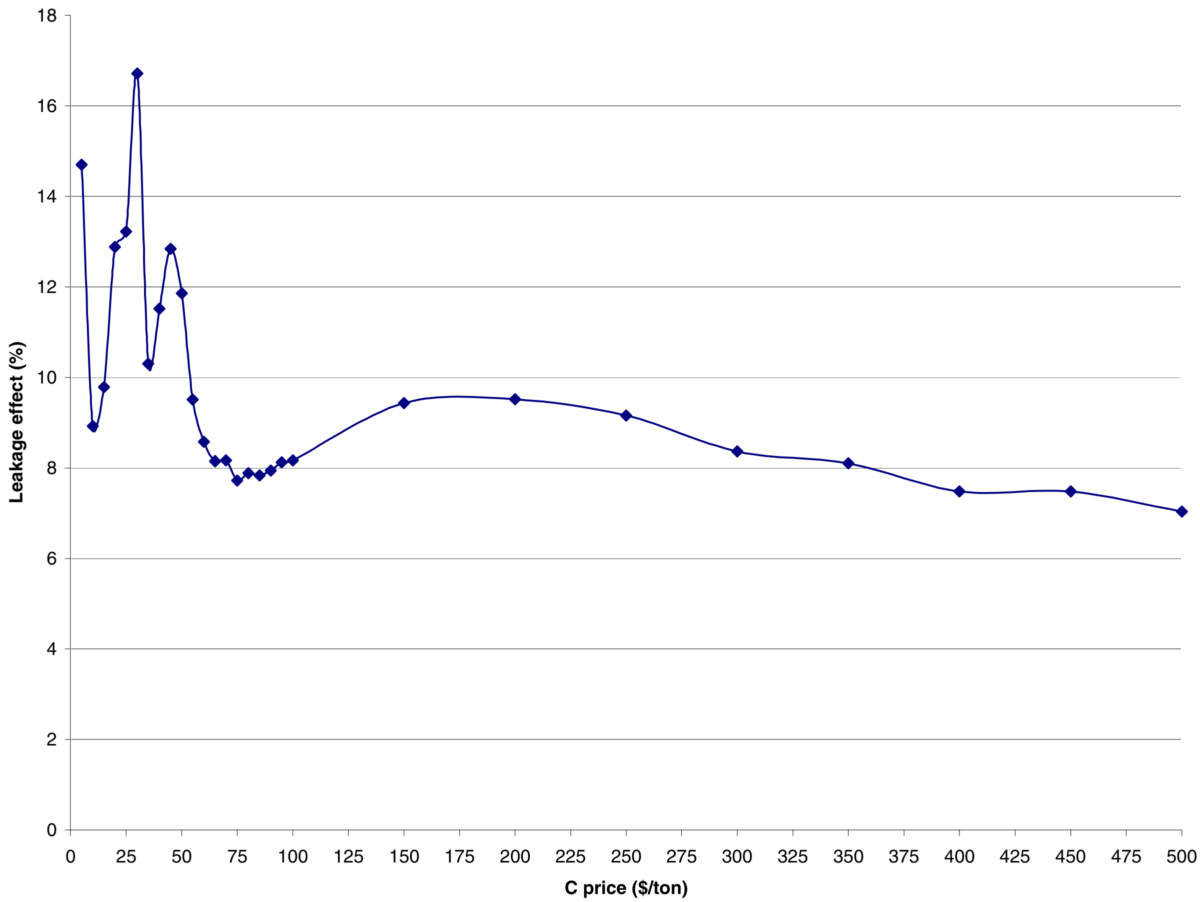


Figure 2. Leakage Effects as a Function of the Carbon Price; Afforestation-Avoided Deforestation Scenario



Appendix A: Derivation of the Leakage Parameter for Forest Preservation

For a forest preservation project, the leakage coefficient equals the ratio of the change in carbon released by harvests diverted to off-project lands divided by the carbon protected on the reserved forest, multiplied by 100 to express in percentage terms

$$L = \frac{dQ_N * C_N}{Q_{R0} * C_R} *100 \qquad \text{(A.1)}$$

where

dQ_N = Change in timber harvested on non-reserved lands

Q_{R0} = Baseline market quantity of timber removed from the market by the preservation project

C_N = Discounted stream of carbon released per unit of harvest on non-reserved forests

C_R = Discounted stream of sequestered per unit of (foregone) harvest on reserved forests

To calculate leakage, we must simulate the change in market for the non-reserved timber. We start by characterizing the effect on the demand for non-reserved timber. The change in the residual demand (see Figure 1 and the main text) facing the producers of non-reserved timber is

$$dQ_N^D = \gamma*\phi*Q_{N0} + E*(1 + \gamma*\phi)*Q_{N0}*(dP/P) \qquad \text{(A.2)}$$

where

Q_N^D = Quantity demanded of the non-reserved timber

Q_{N0} = Baseline market quantity of non-reserved timber

γ = parameter of substitutability between reserved an unreserved timber (=1 if perfect substitutes; 0 if not substitutable)

ϕ = policy scale parameter, equal to the baseline ratio of the reserved timber to unreserved (Q_{R0}/Q_{N0})

E = Price elasticity of demand

P = Market price

The first term on the right hand side reflects the outward shift in N's demand function given the removal of reserved (R) timber from the market. The second term reflects how demanders will respond to the change in the market price. The change in quantity supplied by non-affected producers is

$$dQ_N^S = e*Q_{N0}*(dP/P) \qquad \text{(A.3)}$$

To impose market equilibrium, we set (A.2) and (A.3) equal to each other and solve for the proportional change in the equilibrium price. The market quantity term cancels out and thus we get the change in price expressed as a function of market parameters

$$dP/P = \frac{\gamma * \phi}{e - E*(1 + \gamma * \phi)} \qquad \text{(A.4)}$$

We can then make the following substitution of (A.4) into (A.3)

$$dQN = dQ^S_N = \frac{e*Q_{N0} * \gamma * \phi}{e - E*(1 + \gamma * \phi)} \qquad \text{(A.5)}$$

Setting $Q_{R0} = \phi * Q_{N0}$, substituting (A.5) into (A.1), and manipulating the algebra expresses leakage entirely as a function of the exogenous parameters

$$L = 100 * \frac{e * \gamma * C_N}{e - E*(1 + \gamma * \phi) * C_R} \qquad \text{(A.6)}$$

Note that in the first case in the main text (perfect substitutes), $\gamma = 1$ and thus drops out of the expression in Equation (7) in the main text.

Appendix B: Derivation of the Export Demand Elasticity

The export demand elasticity is defined

$$E_S^X = (\partial Q_S^{DX} / \partial P)*(P/Q_S^{DX}) \quad \text{(B.1)}$$

See the main text for a definition of the notation.

Given equation (10) in the main text, we can derive the export elasticity as follows

$$\begin{aligned} E_S^X &= (\partial Q_W^D/\partial P)*(P/Q_S^{DX}) - (\partial Q_{ROW}^S/\partial P)*(P/Q_S^{DX}) \\ &= (\partial Q_W^D/\partial P)*(P/Q_W^D)*(Q_W^D/P)*(P/Q_S^{DX}) \\ &- (\partial Q_{ROW}^S/\partial P)*(P/Q_{ROW}^S)*(Q_{ROW}^S/P)*(P/Q_S^{DX}) \end{aligned} \quad \text{(B.2)}$$

Defining the world demand elasticity as $E_W = (\partial Q_W^D/\partial P)*(P/Q_W^D)$, and the supply elasticity from the rest of the world as $e_{row} = (\partial Q_{ROW}^S/\partial P)*(P/Q_{ROW}^S)$, we can derive the following expression for the export elasticity

$$\begin{aligned} E_S^X &= E_W*(Q_W^D/Q_S^{DX}) - e_{row}*(Q_{ROW}^S/Q_S^{DX}) \\ &= E_W*(1/H_S^X) - e_{row}*(1/H_S^W) \end{aligned} \quad \text{(B.3)}$$

where H_S^X is the share of country i exports in total world consumption and H_S^W is the ratio of country i's exports to total rest of world production.