2004

2004-3 Estimating Leakage from Forest Carbon Sequestration Programs

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March 2003

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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-reserved 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. These results suggest that leakage effects should not be ignored in accounting for the net level of greenhouse gas offsets from land use change and forestry mitigation activities.

I. 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 to 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 or establish new forests 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 mitigating 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; Bush 2002).

As policy proposals to mitigate climate change have evolved from the 1992 United Nations Earth Summit in Rio de Janiero, it has become clear that, at least in the short run, restrictions on the emission of greenhouse gases (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, although these 38 counties constituted a majority of the world's GHGE in 1990. In addition, countries such as the U.S., which have elected not to participate in the KP currently, are contemplating unilateral emission reduction efforts that would not be coordinated with actions in the rest of the world. The partial coverage implied by the KP or the unilateral actions opens up the possibility that reductions in the countries reducing emissions would be offset, at least in part, by an induced increase in economic activity in countries not pursuing such actions. This is the concept of *leakage* as has been defined and discussed in the Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report (IPCC 2001).[1] 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 GHGE-reducing actions and should be considered when designing and evaluating policies.

A few 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. Second, increased attention has been 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.[2] The amount of credit the buyer 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 developing an estimation procedure that addresses the magnitude of potential leakage from carbon sequestration projects in the forest sector, including the conversion of land from agriculture to forest (afforestation). Leakage is prominent among the concerns often raised about forest carbon sequestration projects as a GHG mitigation strategy by environmental advocacy groups (e.g., Greenpeace 2000; Climate Action Network 1999), and there is wide recognition that leakage should be deducted from the carbon credits granted to a mitigation project (IPCC 2000). President Bush's 2002 Global Climate Change Initiative specifically directs the Department of Agriculture (USDA), the Environmental Protection Agency, and the Department of Energy to develop accounting rules and guidelines for crediting carbon sequestration projects. Yet there is very little empirical evidence on the magnitude of leakage and therefore very little basis on which to calculate the size of the leakage deduction for a representative forest carbon sequestration project. Our objective in this paper is to provide an estimation framework based on economic principles and some empirical evidence on the likely extent of leakage from these types of activities. Specifically, we seek to explain the following:

- interaction of market forces that cause leakage from forest-sector projects,
- key parameters that determine the magnitude of leakage, and
- approximate extent of leakage under different empirical conditions.

II. RELATED LITERATURE

Although this paper focuses on leakage potential from forestry projects, it is helpful to first view the leakage problem more broadly and to 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.
2. A unilateral policy on behalf of a coalition of countries constraining emissions may lower world demand for carbon-intensive fuels, thereby reducing 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 in the energy sector (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 5 to 20 percent of targeted country emission reductions (IPCC 2001). In the case of agriculture, modeling shows that unilateral implementation of the KP in the U.S. could lead to a decline in U.S. exports and an increase in production in the rest of the world, which is indicative of leakage (Lee et al. 2000; Lee 2002).

Perhaps some of the most empirically relevant studies for addressing leakage potential 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 they 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). Wear and Murray (2003) indirectly address the leakage issue by estimating the magnitude of extra-regional feedback from region-specific forest preservation policies. The feedback effects are large, although denominated in softwood lumber units not in carbon. That study is featured in more detail below.

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. A study by Alig et al. (1997) uses a model of the U.S. forest and agricultural sectors to evaluate the net effects of certain forest carbon sequestration strategies such as afforestation. Although 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.

Recent papers have addressed the issue of leakage in forestry and land use climate mitigation projects by either inferring the magnitude of leakage potential analytically (Chomitz 2002), synthesizing the results of studies addressing phenomena similar to leakage (Schwarze et al. 2002), or qualitatively assessing leakage potential and assigning ad hoc values for the leakage deduction (Aukland et al. 2003; Geres and Michaelowa 2002). 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). Defining leakage in terms related to economic theory and expressing leakage as a mathematical expression of key economic and biophysical variables—an approach followed by Chomitz and a path we follow here as well—are important first steps. However, we go beyond that point here by employing data and models to estimate directly the magnitude of leakage for a range of specific forest carbon sequestration activities across different regions in the U.S. By quantifying leakage effects for these activities and regions, we can take a step forward in assessing project credits for projects with similar characteristics.

III. A MODEL FOR MEASURING LEAKAGE FROM A FOREST PRESERVATION PROJECT

To further explain leakage concepts, we first use an analytic model that 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 the harvest restriction.

III.1 Reserved and Non-reserved Timber as Perfect Substitutes

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

$$Q_R^S = Q_R^S\,(P, W_R, I_R) \qquad [1]$$

$$Q_N^S = Q_N^S\,(P, W_N, I_N) \qquad [2]$$

where Q_k^S (k = R, N) 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 the supply source where R identifies supply from sources potentially targeted by a forest preservation program, and N identifies supply from outside the potentially reserved lands. Although we omit a time subscript, the supply function is conditional on the harvestable inventory (I_k) and price signals applicable at a given point in time.[3]

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

$$Q^D = Q^D(P, Z), \qquad [3]$$

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:

$$Q_N^S\,(P^*, W_N, I_N) + Q_R^S\,(P^*, W_R, I_R) = Q^D\,(P^*, Z). \qquad [4]$$

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:

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

Inserting [5] into the equilibrium condition [4], produces an equilibrium for segment N of

$$Q_N^S\,(P^*, W_N, I_N) = Q_N^D\,(P^*, Z, W_R, I_R). \qquad [6]$$

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 [$Q_{R0} = Q^S_R (P_0, W_R, I_R)$]. 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. 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. Let's 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. Comparative statics can be performed on the market equilibrium system defined by equations [1] through [6] to derive a mathematical expression for the leakage effect as a function of the exogenous parameters (see Murray et al. 2002, Appendix A, for the derivation). That expression is

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

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.

Consider a case in which supply and demand elasticities are unitary elastic ($e = 1$ $E = -1$), the magnitude of the timber restriction is non-trivial ($\phi = 0.10$), and the carbon density of restricted (CR) and non-restricted forests (CN) is identical. With these parameter values, the leakage estimate is 47 percent, indicating that about half of the carbon retained on the reserved forests is offset by carbon released through displaced harvests. Differentiation of equation [7] reveals that leakage is enhanced the more responsive suppliers are to price ($dL/de > 0$), the less responsive demanders are to price ($dL/d|E| < 0$), and the higher the ratio between carbon density on non-restricted forests to restricted forests ($dL/d[CN/CR] > 0$). Moreover, leakage is proportionately larger when the relative size of the restriction falls ($dL/d\phi < 0$). This runs counter to the notion that leakage is less of a problem for small isolated projects than it is for larger (e.g., national-scale) programs and can thus simply be ignored. In absolute terms, of course, leakage will be smaller when the policy itself is limited. However, the relevant issue here is how large leakage is in proportion to carbon enhancement on the forest targeted by the policy. The result, $dL/d\phi < 0$, implies that smaller interventions have larger proportional leakage effects. Thus, ignoring leakage at the project level is not a prudent option. We will return to this below.

III.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 assumption above could introduce upward leakage estimate biases because it tends to maximize the extent to which the market would simply relocate the harvests. We therefore relax the perfect substitution assumption 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

$$\Omega_{RDN} = \gamma Q_{R0}, \qquad [8]$$

where Ω_{RDN} 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 eliminating 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.[4]

Figure 1 (perfect substitutability between R and N timber) reflects the case of $\gamma = 1$. If $\gamma = 0.5$, the products are moderate substitutes, and 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 Murray et al. 2002, Appendix A):

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

Differentiation of [9] shows that the leakage is enhanced by the degree of substitutability ($dL'/d\gamma > 0$).

III.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, for example, 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. As shown above, more elastic demand diminishes leakage ($dL/d|E|<0$), thereby suggesting, at first glance, that a forest preservation project in a small country facing a large global market would have little or no leakage. We believe the no-leakage implication is correct, but only within the country. No leakage occurs within a country because the export price determines the amount of timber supplied by that country and that price will not be 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 implies leakage could occur on a large scale. The world market for timber tends toward fairly inelastic aggregate demand (Sohngen et al. 1999), but the small country's share of the world market 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_S^{DX}) can be expressed as a function of total world demand (Q_W^D) and the amount supplied by the rest of the world (Q_{ROW}^S), both of which are a function of the world (export) price (P):[5]

$$Q_S^{DX} = Q_W^D (P) - Q_{ROW}^S (P). \qquad [10]$$

It can readily be shown (see Murray et al. 2002, Appendix B) that the demand elasticity facing small country S (E_S^X) 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's exports in total world consumption (H_S^X), and the ratio of country i's exports to total rest-of-world production (H_S^W):

$$E_S^X = E_W (1/ H_S^X) - e_{row}(1 / H_S^W). \qquad [11]$$

This shows that country S'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. For instance, under a world demand elasticity of –1.0, a world supply elasticity of +1.0, and country s's export share of the world market of 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's exports without a noticeable effect on world price. In other words, an elastic demand facing country S suggests there are ample extramural leakage opportunities when country S reduces production in the name of sequestration.

To evaluate the magnitude of leakage in such cases, one would either need an integrated model of global forest products trade and carbon accounting or 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, but we could proxy for these global effects by treating the isolated forest preservation project as if it caused a very small increase in the residual demand function for unreserved forests (i.e., as if the size of the market shock caused by the preservation action is very small relative to the world market). But, as shown above, smaller shocks have larger proportional leakage effects, all else equal ($dL/d\phi < 0$), thereby supporting the view 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 are 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 above, 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.

III.4 Do the Leakage Examples Above Hold Up Empirically? An Examination of Forest Preservation in the U.S. Pacific Northwest

To empirically test 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 from national forests that were implemented in the 1990s. During a 10-year time period, the volume of Pacific Northwest (PNW) timber harvested from public lands was reduced by about 85 percent and has remained low since then. 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 (2003) examined the timber restrictions to see the extent to which they induced harvests in other timber supply regions within North America (i.e., leakage). Wear and Murray 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.

Table 1 summarizes Wear and Murray's results, which can be viewed as a crude indicator of leakage using timber production, rather than carbon, as the displaced commodity (Wear and Murray did not directly address carbon matters). The average annual federal timber harvest reduction in the U.S. West for the period 1990 to 1995 was approximately 2.1 billion board feet. However, Wear and Murray 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 and was replaced by other regionally induced harvests. The leakage effect increases when we expand the effects in the U.S. South and Canada. Wear and Murray estimate an additional 300 million board foot harvest response, raising the continental U.S. leakage estimate to 58 percent. Finally, Wear and Murray estimate a 550 million board foot response in Canada, resulting in a North American continental scale leakage estimate of 84 percent. If we compute the forecasted leakage using the formula above (equation 7) with parameters derived from the Wear and Murray model ($e = +0.46$ – a weighted average of all four supply regions, $E = -0.06$, $\phi = 0.045$) we get a predicted leakage level of 87 percent, indicating close correspondence between leakage model predictions and actual observations.

IV. BROADER EXAMINATION OF LEAKAGE—A MULTI-SECTOR, INTERTEMPORAL SIMULATION

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 clearing land, especially in developing countries, is agricultural expansion. If a forest 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 here 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.

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, 1999) 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 mathematical programming methods to maximize 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 U.S. is divided into 11 regions and includes 48 primary and 45 secondary commodities and three forest products. The timber growth depends on 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 GHG accounting in FASOM accounts for terrestrial carbon in forest ecosystems on existing forest stands, regenerated and afforested stands, non-commercial carbon pools after harvest, harvested timber products, and agricultural lands (Lee 2002, Schneider 2000, McCarl and Schneider 2001). The modified version of FASOM was solved repeatedly by adding additional policy constraints in each case listed below.

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 PNW 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: preserved without harvest or 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 KP.

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 on carbon quantity effects. We modify the leakage measures from the analytical model above to account for the intertemporal dimension of carbon flows:

$$L^T = [(PV_P - PV_T)/PV_P]*100. \qquad [12]$$

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:

$$PV_j = \sum_{t=1}^{T} \frac{c_{jt}}{(1 + r)^t}. \qquad [13]$$

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.

IV.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 PNW (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 by 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. Setting aside old-growth forest in the PNWW diverts harvests to other regions, such as the SC, where the forests are typically younger and more uniform; hence, the carbon losses from harvest will not be as large as the carbon savings in the PNWW. Conversely, protecting a relatively less carbon-dense forest in the South diverts harvests to the more carbon-rich PNWW, potentially causing large leakage effects.

IV.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 2 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 PNW east side (PNWE), again suggesting that actions to 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. In particular when harvesting is allowed on these lands, we do not find that harvests are shifted as much outside the reserved area. However, allowing harvest also means that less carbon is sequestered on the targeted lands.

The FASOM result shows negative leakage in the Corn Belt/harvesting allowed example. Activities on targeted lands in that region 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 amount of negative leakage 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.

IV.3 Afforestation Program Results

Table 3 presents the results of a fairly large (10 million acre) afforestation program converting land from agriculture to forests applied in different regions. We run these scenarios separately (e.g., only one program is in effect for each run of FASOM) for selected regions (those that have had some history of large-scale movement of land between agriculture and forestry). 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, because 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.

IV.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 in the U.S. 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 constitute 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 a wide range of carbon prices ($5 to 500 per tonne, carbon equivalent). 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.[6] Because the scale of the targeted program is larger at higher prices (i.e., there is greater participation when the incentives are higher), this provides some further evidence that leakage effects are proportionately higher the smaller the program (or project).

V. CONCLUSIONS

This paper uses economic principles, data, and methods to frame the leakage issue in the context of forest-sector climate mitigation projects (including afforestation of agricultural lands). We find that, under some circumstances, leakage from geographically targeted mitigation projects can be sizeable and in other cases it is not. It is commonly argued that small projects will have negligible effects on the affected markets and therefore generate little leakage. Our results suggest otherwise. For small projects, leakage may be small in absolute terms, but it tends to be larger in proportion to the direct project benefits than a larger program or policy. Thus, leakage outside the boundaries of even small projects should not be ignored.

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. Because 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.

Although 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. Throughout the nascent literature on leakage referenced above, researchers have wondered whether leakage in forest carbon projects is systematically larger or smaller than energy-sector leakage. The empirical results here suggest that forest carbon leakage may be somewhat larger than the energy sector estimates (previously cited as roughly 5 to 20 percent), although part of this gap could be due to differences in the methods used across studies. If indeed leakage is more pronounced in forest carbon projects than energy-sector projects, this could affect the terms of trade for the credits generated by different sources and thereby affect the optimal portfolio of mitigation options. A clear implication of this is that policy designers and market makers should adequately account for leakage effects when enabling exchanges of GHG offsets.

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[1]The phenomenon described here has been referred to by other names, including “slippage,” “rebound effect,” and more generally “crowding.” But “leakage” is the prevalent term for this effect in climate policy.

[2]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.

[3]The inclusion of a quasi-fixed capital stock variable on the right-hand side classifies these as short-run timber supply functions as defined by Wear and Parks (1994).

[4]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.

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

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

Table 1. Estimated Harvest Leakage Effects from Federal Timber Restrictions in the U.S. Pacific Northwest (from Wear and Murray [2003])

Public Harvest Timber Reductions	Million Board Feet[a]	
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 2. Avoided Deforestation Leakage Results (All Quantities Are Percentages)

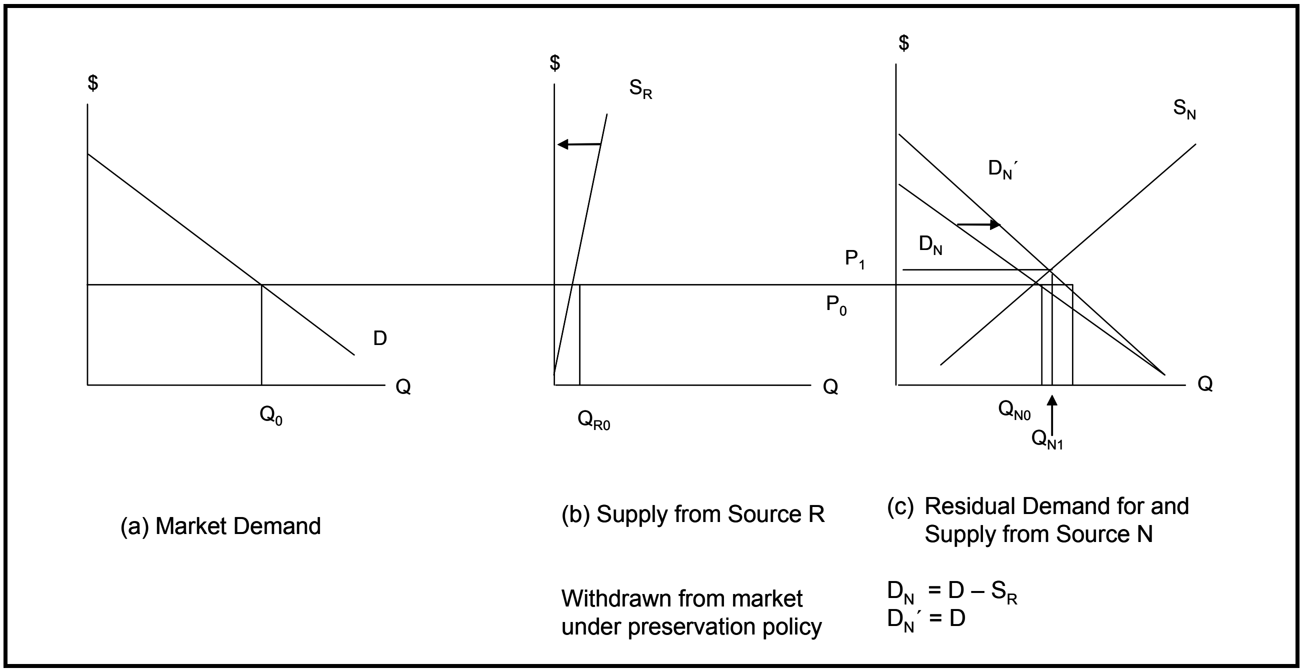
Region	No Harvesting Allowed	Harvesting Allowed
Pacific Northwest—east side	8.9	7.9
Northeast	43.1	41.4
Lake states	92.2	73.4
Corn Belt	31.5	–4.4
South-Central	28.8	21.3

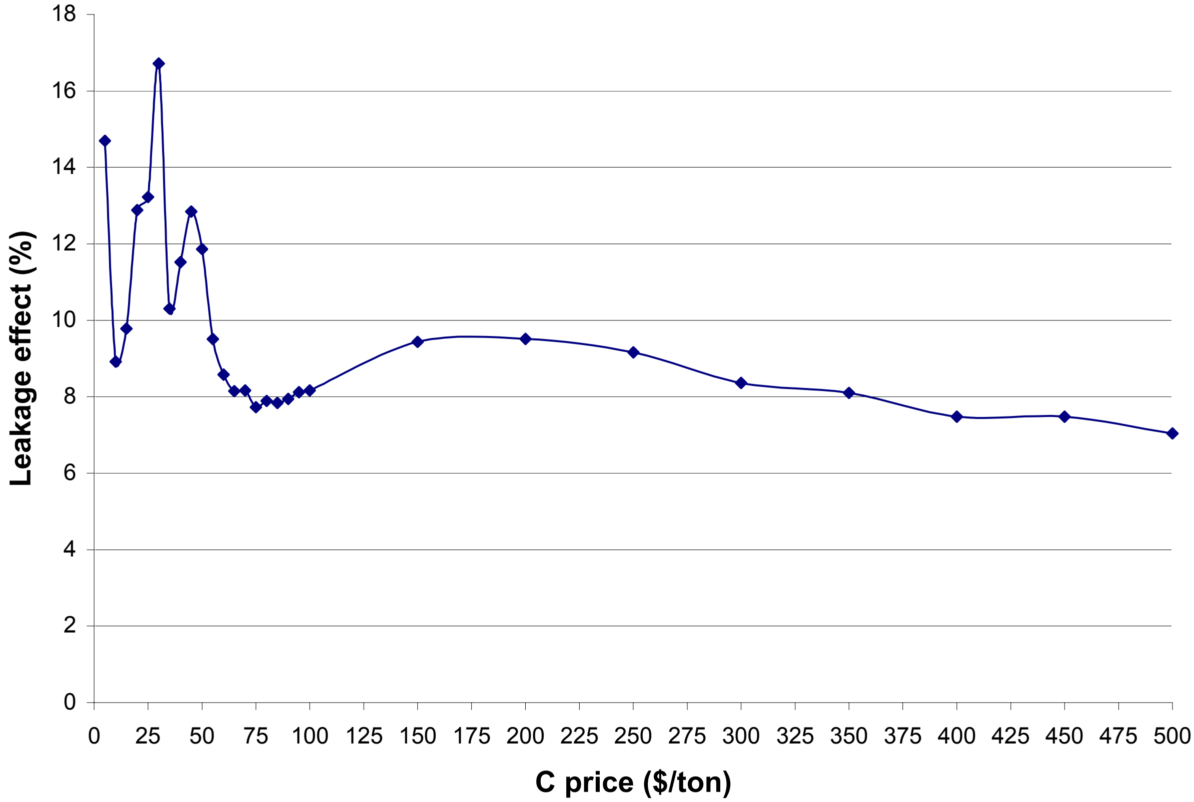
Table 3. Afforestation Program Leakage Estimates by Region (All Quantities Are Percentages)

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


$
$
S_R
$
S_N
D_N´
P_1
D_N
P_0
D
Q
Q
Q
Q_0
Q_R0
Q_N0
Q_N1
(a) Market Demand
(b) Supply from Source R
(c) Residual Demand for and Supply from Source N
Withdrawn from market under preservation policy
D_N = D – S_R
D_N´ = D



Leakage effect (%)
C price ($/ton)
0
2
4
6
8
10
12
14
16
18
0 25 50 75 100 125 150 175 200 225 250 275 300 325 350 375 400 425 450 475 500