Measuring leakage from carbon projects in open economies: a stop timber harvesting project in Bolivia as a case study

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Abstract: This paper develops methods for estimating leakage from forest-based carbon projects that seek to reduce carbon emissions from timber harvesting in tropical forests. A theoretical framework is presented in which a specific country, in this case Bolivia, is treated as a supplier to the global timber market. Leakage is measured, over a 30- to 50-year time period, as the difference in net national carbon emissions from timber harvesting between the baseline case and a scenario in which some of the land is removed from the concession base. Estimates of timber leakage are made for several different assumptions about future global sequestration policies, capital constraints, demand elasticity, and deadwood decomposition rates. The results suggest that leakage could range from 5% to 42% without discounting carbon, and from 2% to 38% when carbon is discounted. Demand elasticity and wood decomposition rates have the largest effects on the leakage calculation. Leakage is lowest when demand is more elastic and wood decomposition rates are faster, and vice-versa when these conditions are reversed. Leakage appears to be sensitive to capital constraints only when project benefits are measured over a shorter time period.

Résumé : En vue de réduire les émissions de carbone résultant de la récolte du bois dans les forêts tropicales, cet article expose le développement de méthodes d'estimation des fuites de carbone issues de projets forestiers. On y présente un cadre théorique dans lequel un pays donné, la Bolivie par exemple, est considéré comme un fournisseur de bois sur le marché mondial. Mesurées sur période de 30 à 50 ans, les fuites de carbone dans les émissions nationales nettes liées à la récolte forestière correspondent à la différence entre un scénario de référence et un scénario dans lequel la base territoriale attribuable en concession est amputée. Les estimations du niveau des fuites sont effectuées pour plusieurs jeux d'hypothèses concernant les politiques futures de séquestration à l'échelle mondiale, les contraintes en capital, l'élasticité de la demande et les taux de décomposition des bois morts. Les résultats obtenus suggèrent que le niveau des fuites pourrait varier de 5 à 42 % sans escompter le carbone et de 2 à 38 % quand il est escompté. L'élasticité de la demande et les taux de décomposition du bois ont les effets les plus marqués sur le calcul du niveau des fuites. Ce niveau est le plus bas quand la demande est élastique et que les taux de décomposition sont élevés. C'est le contraire quand ces conditions affichent les tendances inverses. Le niveau des fuites semble sensible aux contraintes en capital seulement quand les bénéfices des projets sont mesurés sur une courte période de temps.

[Traduit par la Rédaction]

Introduction

The global carbon cycle is significantly influenced by changes in the use and management of forests and agricultural land. Recognition of the role that humans play in land-use change and management and that policies could potentially enhance carbon sequestration led to the inclusion of carbon "sinks" in the Kyoto Protocol (see articles 3.3, 3.4, 6, and 12). While a recent decision on the Clean Development Mechanism (article 12) has limited land-use change and forestry (LUCF) activities to afforestation and reforestation (UNFCCC 2001), for the time being, non-Kyoto countries, such as the United States and Australia, can potentially utilize alternative methods for sequestering carbon, such as stopping logging or engaging in sustainable forestry. Controversy over the environmental integrity of these methods, however, has arisen. In particular, one of the most challenging technical issues for LUCF projects is the identification and monitoring of leakage (Brown et al. 2000*a*). While the potential for leakage does not necessarily make a project unattractive, strategies need to be developed to mitigate and (or) account for leakage. This paper presents a methodology for analyzing leakage in carbon projects that focus on stopping forest harvesting in a developing country, namely Bolivia.

Leakage occurs when adjustments in relative prices reduce the intended impact of a policy. For example, the buyout of dairy herds in the United States in 1980s was found to reduce overall dairy herd size and production for a time, but had limited long-term effects because of the resulting price changes (Dixon et al. 1991; Bausell et al. 1992). Wu (2000) examined the United States Conservation Reserve Program that retired highly erodable land and found that each hectare added to the program reduced cropland

Received 24 March 2003. Accepted 17 October 2003. Published on the NRC Research Press Web site at http://cjfr.nrc.ca on 16 April 2004.

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 doi: 10.1139/X03-249

area by only 80% in the region of interest, that is, there was 20% leakage. A global forest market simulation model by Sohngen et al. (1999) suggests that forest set-asides in the United States and Europe would also have leakage, albeit relatively small (for every 20-ha set-aside, 1 ha of inaccessible land elsewhere would be accessed). Efficiency losses, however, can also occur in related sectors. Stavins and Jaffe (1990) showed how flood control projects cause externalities through losses in wetlands, and Henry et al. (1993) showed that the dairy buyouts in the 1980s caused welfare losses in the beef cattle industry.

Within carbon policy, there is substantial uncertainty and discussion about the potential for leakage (i.e., Kauppi and Sedjo 2001; Watson et al. 2000). Although carbon leakage has been discussed within the energy sector, most of the discussion centers on the limited global extent of policy making. By focusing on only certain countries, reductions made under the Kyoto Protocol could leak to other regions if economic activity (and consequently energy production) shifts. Potential leakage in the energy sector was estimated to be 0%–70% in the Intergovernmental Panel on Climate Change (IPCC) Second Assessment Report to a more modest 5%–20% in the IPCC Third Assessment Report (Hourcade and Shukla 2001).

Land-use-change and forestry mitigation may similarly cause shifts in economy-wide or global forest and agricultural activity if the programs affect a large proportion of global timber production and consequently prices. Alig et al. (1997) used a simulation model of the United States forest and agricultural sectors to show that in a large United States program involving afforestation, for every hectare of land converted to forests, one hectare would potentially be converted from forests to agriculture elsewhere. A more recent study of carbon leakage by Murray et al. (2004) suggests that the carbon leakage from afforestation or reduced deforestation projects in the United States could range from 10% to 90%, depending on the region where the project is undertaken. While there has been intensive study of carbon projects in the United States, to date there have been few attempts to estimate leakage in carbon projects in developing tropical countries (Chomitz 2002).

Measuring the leakage that may arise from projects in developing countries remains difficult, however. First, empirical data that could be used to estimate the effect of a project on nearby land or within a country are often unavailable. Second, projects often involve relatively small land areas and relatively small carbon flows, and separating these small changes from larger regional, national, or global statistics on harvesting or land-use change is difficult. Third, the geographic scale over which leakage should be measured is not described in the policies defined for measuring it, although carbon is clearly a global externality. For this paper, we assume that a country's responsibility for carbon leakage stops at its border, and we model export demand as perfectly elastic. This assumption means that we do not calculate potential leakage outside of Bolivia. Fourth, although the extent of global sequestration projects remains uncertain, the growing number of worldwide projects could influence the project baseline. For example, if the world undertakes many carbon sequestration projects in the next 50 or 100 years, timber prices may change substantially (Sohngen and Mendelsohn 2003). Individual projects should account for the effects of these external projects on their baseline and leakage estimates.

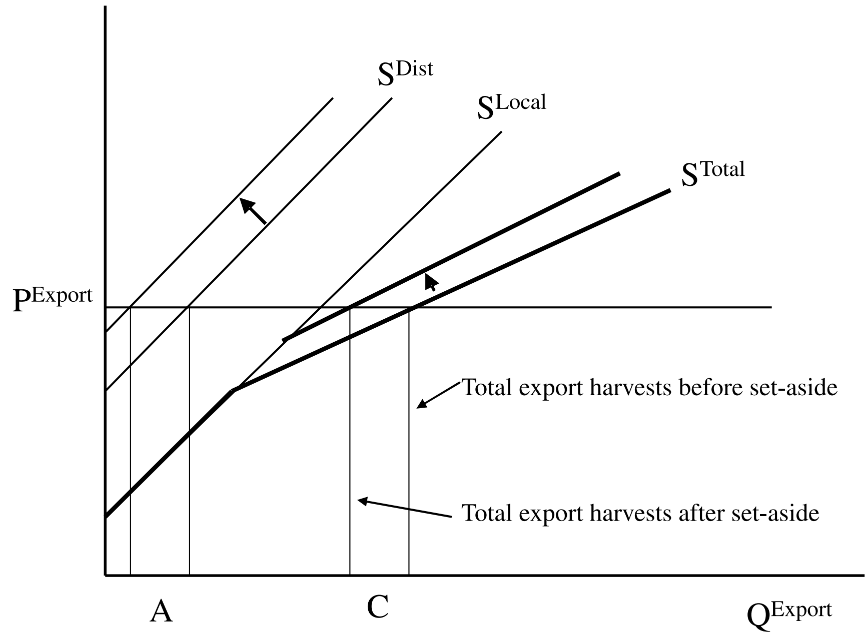
This paper addresses these issues by presenting the results of research undertaken to estimate potential leakage arising from a carbon project in Bolivia. A main activity of the Noel Kempff Mercado Climate Action Project (NKCAP) involved buying out the timber concession rights and forestry equipment on about 661 000 ha of land (79% of which is productive timberland) adjacent to the Noel Kempff National Park in Bolivia in 1996 (more details of the project are given in Brown et al. (2000*b*)). To measure leakage, a dynamic optimization model of Bolivian timber markets is constructed. The model simulates harvests from the indemnified concessions, as well as from concessions in other forestry regions of the country. An internal demand function is specified to model the market within Bolivia, while export prices are given exogenously, and Bolivia is assumed to be a price taker on the global market. To account for the potential effects of carbon projects elsewhere in the world, export timber prices are linked to a study that analyzes global sequestration policy (Sohngen and Mendelsohn 2003).

The effects of stopping logging in a small open economy

In many developing countries, timber is harvested from concessions that give timber companies or mills the right to harvest for a number of years on that piece of land. Within Bolivia, the country of interest for this study, concessions are often granted for 40 or more years. Aukland et al. (2003) suggest that projects that remove concessions from the timberland base have two potential types of leakage: (1) primary leakage, or activity shifting that occurs when capital and labor are freed through a project's activities, and (2) secondary leakage, or market effects that occur when prices change and cause other market actors to shift. The contracts for NKCAP focused initially on avoiding primary leakage by removing the concessions and the capital (i.e., the equipment used to harvest trees and transport timber to market) associated with those concessions from the market and by indemnifying the former operators from legally engaging in timber market activities for a number of years. This study assesses potential leakage associated with secondary market adjustments.

For the analysis, Bolivia is assumed to be a small open economy that is a price taker on global timber markets. This is the most likely case for Bolivia, given that it produces less than 0.5% of the total industrial roundwood produced in South America (FAOSTATS 2001) and exports less than 0.5% of the total industrial roundwood exports in the region. It is slightly more important for export of manufactured wood products in South America, as it exports 1% of the total exported manufactured products (i.e., boards and plywood). To model Bolivia as a price taker, a perfectly elastic export demand function is used in the timber market model, so that any policy enacted within Bolivia that affects supply will have no effect on global prices (Fig. 1). Two supply regions, a distant region from the export center and a close region, and the aggregate supply function are shown. A reduction in supply from the distant region reduces the total

Fig. 1. Bolivian export market with two internal supply regions. S^{Dist} is the supply from a region distantly located from the export market, S^{Local} is the supply from a region close to the export market, S^{Total} is the sum of the two supplies, and P^{Export} is the export price.



supply of wood products from Bolivia to the world economy, but it does not affect global prices. Thus, if the baseline-projected reductions in harvests are measured as "A" in Fig. 1, the net national reduction will be the same size, shown as area "C".

While the country is likely to be a price taker on export markets, a domestic market for Bolivian timber products exists (Merry and Carter 2001). Internal markets for Bolivian timber products amount to roughly 50% of the exports from the country. For the most part, species used internally are typically lower quality than the wood that is exported. In this paper, it is assumed that wood used internally and for export are not perfect substitutes. Bolivia imports no wood (FAOSTATS 2001), and the market has a downward sloping demand function for domestic consumption (Merry and Carter 2001). The effect of the supply shock on the internal market is shown in Fig. 2. While the total effect of the project is area "B" in Fig. 2, the net effect is area "D". Moving up the domestic demand function reduces the net effect of the project. Reducing supply and raising prices increase the incentives concessions have for producing wood for internal markets.

While Figs. 1 and 2 give a general picture of changes that may occur with a set-aside for carbon sequestration, carbon projects often entail carbon benefits for many years. For instance, in the NKCAP, reductions in harvesting are to be calculated for a 30-year time period. Not only is the baseline likely to change over time in response to global changes in prices and changes in the internal demand for products, but the set-asides themselves can have dynamic effects that are felt over many years. Changing prices could alter the path of investment in other regions and consequently the quantity of timber harvested. It is important to measure the potential leakage effects in a dynamic rather than static context.

Perhaps more importantly for carbon policy, the NKCAP project is likely to be one of many similar projects or country-wide policies throughout the world, each of which will affect global timber supply and prices. Given the small size of NKCAP project and Bolivia's timber exports, the price changes caused by sequestration projects elsewhere are likely to be more important for Bolivia than the effect of the Bolivian project on global prices. Of course, linking our results to global sequestration results requires making an assumption about the future course of global sequestration projects. For this paper, we follow the set of global sequestration programs described in Sohngen and Mendelsohn (2003). That study showed the timber market implications of two global sequestration programs that sequester 13×10^9 to 34×10^9 t carbon on 190×10^6 to 488×10^6 ha of additional forestland of carbon by 2050. The timber price implications of these scenarios are shown as the low and high scenarios in Fig. 3.

Modeling Bolivian timber markets

To capture leakage effects from the NKCAP project in Bolivia, a dynamic optimization model of timber markets in Bolivia is developed, following similar efforts in Sohngen et al. (1999), Alig et al. (1997), and others. The direct project area is modeled within the context of a national market, so that the potential pathway of future harvests in Bolivia, both in the project area and within the entire country, is simulated. The model has a 125-year time horizon, although only the first 50 years are presented in this analysis. One implication of the results of Merry and Carter (2001) is that the investment of capital in the forestry sector plays a large role in how much timber is harvested. That is, the industry is more heavily constrained by the capital that is invested in the forestry sector than by the area of forestland available for concessions. It is important in Bolivia to model not just the progression of harvests over time, but also to model investments in harvesting and processing capital, as suggested by Lyon et al. (1987).

Fig. 2. Bolivian internal market with two internal supply regions. S^{Dist} is the supply from a region distantly located from the export market, S^{Local} is the supply from a region close to the export market, S^{Total} is the sum of the two supplies, $D^{Internal}$ is the internal demand function, and $P^{Internal}$ is the domestic price for timber set by the equilibrium between supply and demand.

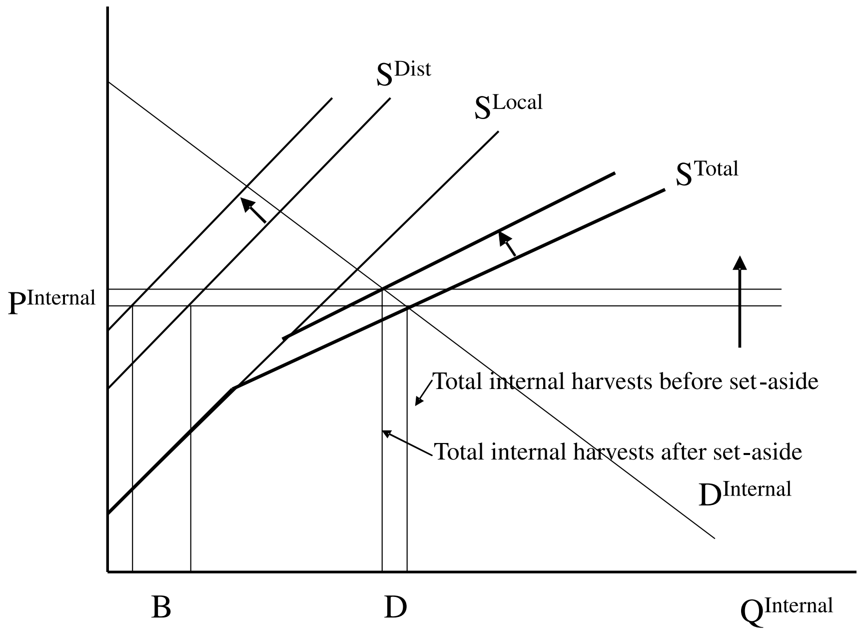
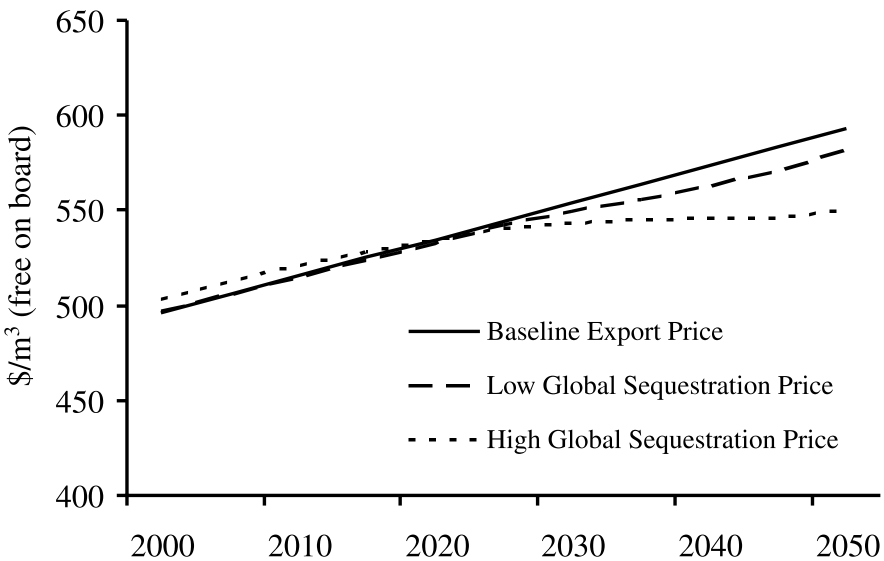


Fig. 3. Export price indices for baseline and two global carbon sequestration scenarios.



We begin by assuming that two types of timber products are produced in Bolivia, high-quality timber for export and lower-quality timber for internal markets. Export demand is governed by a perfectly elastic export demand function, and domestic demand is assumed to have an elasticity of –1.3. This estimate is consistent with the recent results of Merry and Carter (2001), who suggested that domestic demand elasticity ranges from –0.9 to –1.5. At time t, therefore, the Bolivian timber market attempts to maximize social welfare, S_t:

$$[1] \qquad S_t = P_t^E q_t^E + \int_0^{\alpha_t q_t^E} [D(n_t, Z_t)]\, dn_t - CH_t - CK_t - CL_t$$

where P_t^E is the export price at time t, q_t^E is the quantity of export boards, $\alpha_t q_t^E$ is the quantity of boards sold in the domestic market, Z_t is a demand shifter for the domestic Bolivian demand function. For the baseline, export prices are assumed to follow the baseline presented in Sohngen and Mendelsohn (2003). The internal demand function for domestic Bolivian markets is assumed to shift outward at 0.5% per year. CH_t is the cost of harvesting, shipping, and marketing boards; CK_t is the cost of investing in new capital and maintaining existing capital; and CL_t is the cost of additional inputs into the production process. For the empirical application, these costs are obtained from Mancilla (1999).

In the model, domestic markets are supplied as a consequence of satisfying export demand. In Bolivia, as in many tropical forest regions, concessionaires have a choice over both hectares harvested and intensity of harvests. Tropical forests have a wide diversity of species, only some of which are valuable enough to be exported. The remaining species could be used internally, depending on the price for internal timber and the yield of merchantable biomass within the country. Thus, q_t^{E} describes the quantity of timber that is exported, and α_t describes the rate of usage of the additional biomass on sites that are harvested. Note that α_t is constrained, such that $0 \le \alpha_t \le \alpha^*$, where α^* is the maximum biomass yield on timber harvesting sites. Also note that when solving the model, we impose the additional constraint that domestic market prices cannot exceed export market prices. This is an arbitrage condition suggesting that if the value of internal-market products rises above export-market prices, additional boards will be shifted to external markets.

Different sites within the country have concave merchantable timber yield functions of the form $V_{a,t}$, where a is age, and t is time. The yield functions can change over time, for example, because second-growth forests may yield lower quantities of merchantable export timber than old-growth tropical forests. The yield function is given as

$$[2] \qquad V_a = \exp(B_1 - B_2/a)$$

where B_1 and B_2 are parameters, and a is the age-class. Currently, most harvesting in Bolivia occurs in mature forests that have not been accessed before or have been high-graded only. Once timber is extracted from these sites, it is assumed to be available again in the future. The age of harvesting in the future is determined optimally by the timber model. In the initial periods of the model solutions presented below, much of the extraction occurs on mature timber stands. In future periods, extraction also occurs in second-growth stands. Timber extracted from harvesting is assumed to be converted into boards that are sold in export or internal markets.

Following Lyon et al. (1987), the production function for export and internal timber boards is assumed to have the following functional form:

$$[3] \qquad Q_t = AK_t^B L_t^{1-B}$$

where

$$[4] \qquad Q_t = (1 + \alpha_t)q_t^{\mathrm{E}}$$

In eq. 3, A is a constant in the production function, B is a parameter that is assumed to be 0.8, K_t is capital invested in the timber industry, and L_t is a numeraire representing other inputs in the production process, including labor. Production efficiency is assumed to be 50%, so that 50% of the logs harvested can be converted into boards useful for internal or export markets. If the total volume of logs harvested is H_t, then

$$[5] \qquad Q_t \le 0.5H_t = 0.5\left[\sum_a (1+\alpha_t)h_{a,t}^{\mathrm{SG}}V_{a,t} + \sum_a (1+\alpha_t)h_t^{\mathrm{OG}}V^{\mathrm{OG}}\right]$$

where $h_{a,t}^{\mathrm{SG}}$ is the area of second-growth land harvested in age-class a at time t, h_t^{OG} is the area of old-growth stands harvested in time period t, and H_t is the total merchantable log volume.

Our interest in this study is on how the forest sector manages two important stocks, forests and timber processing capital. Equations of motion are required to describe how these stocks will evolve over time. Several equations are required for the movement of timber stocks through time. First, a set of mature forests must be described. These are tropical forests under concession that have likely not been previously harvested. If the stock of mature forests is given as X_t^{OG}, the change in mature forest area over time is given as

$$[6] \qquad X_{t+1}^{\mathrm{OG}} = X_t^{\mathrm{OG}} - h_t^{\mathrm{OG}}$$

Note that it is not necessary to track the age-class of these forests, as they are assumed to hold the maximum potential biomass on the site.

Second-growth stocks are also important in the Bolivian situation. Recent changes in forestry law hold concessionaires to long-term (40+ year) contracts and charge rental rates for the area of land held. Concessionaires have incentives to hold the minimum land possible and maximize their revenues on this land over time. Two equations of motion describe the evolution of these second-growth stocks, $X_{a,t}^{\mathrm{SG}}$:

$$[7] \qquad X_{a+1,t+1}^{\mathrm{SG}} = X_{a,t}^{\mathrm{SG}} - h_{a,t}^{\mathrm{SG}}$$

and

$$[8] \qquad X_{i,1}^{\mathrm{SG}} = \sum h_{a,t}^{\mathrm{SG}} + h_t^{\mathrm{OG}}$$

The equation of motion for timber processing capital is given as

$$[9] \qquad K_{t+1} = (1-d)K_t + I_t$$

where d is depreciation of the capital, and I_t is the annual investment decision.

The timber model for Bolivia is solved by maximizing

$$[10] \qquad \mathrm{Max} \sum_1^{T-1} \rho^t S_t + \rho^T S_T$$

where ρ^t is the discount factor, and T is the terminal time period. Equation 10 is then maximized subject to the constraints given in eqs. 5, 6, 7, 8, and 9. Yield functions are exogenously given, and all choice variables are also constrained to be greater than or equal to 0. The model chooses $h_{a,t}^{\mathrm{OG}}$, $h_{a,t}^{\mathrm{SG}}$, α_t, and I_t.

The terminal conditions are chosen as the steady-state conditions that would evolve at the given price and demand levels 100 years into the future. There continues to be debate about whether or not second-growth forests become normal (i.e., there are equal areas of timber ages in stands of a given concession or forest area) forests at steady state (see Salo and Tahvonen 2002). From a practical modeling perspective, if one is interested only in the first 50 years of the results, imposing a normal or other type of forest on the future steady state 125 years in the future is likely to be irrelevant because of discounting. For this study, we impose the terminal condition in year 125. Thus, while export prices and internal demand are assumed to stabilize at year 100, the forest condition continues to evolve for 25 more years. Steady-state values for each age-class of forests are esti-

Table 1. Regional harvests and concession holdings in 1997 (Quispe and Vaca 2001).

	Harvests		Concession holdings		
Region	1000 m^3	%	1000 ha	%	Harvests per hectare of concession (m^3/ha)
Santa Cruz	356	45	2806	49	0.13
Beni	185	23	891	16	0.21
Cochabamba	113	14	—	—	—
Pando	84	11	1535	27	0.05
La Paz	43	5	400	7	0.11
Total other	16	2	96	2	0.17
Total Bolivia	797	100	5728	100	0.14

mated by assuming a normal forest and deriving optimal capital investments and prices. These steady-state values are then used to value the stock at the terminal period at 125 years, without imposing an additional constraint that all age-classes have equal areas.

Estimating carbon flows and leakage

Net carbon gains associated with setting aside timber concessions are estimated by assessing the carbon emissions associated with harvesting timber under the baseline scenario and under the forest protection (with project) scenario. The carbon accounting model is presented briefly here, and specific details can be found in Brown et al. (2000*b*). Suppose that the baseline path of timber harvesting for Bolivia in years 1 to $T-1$ is $Q^{0*} = (Q_1^{0*}, Q_2^{0*}, \ldots, Q_{T-1}^{0*})$. Annual carbon emissions, C_t^{0*}, are

$$[11] \quad C_t^{0*} = \lambda(1-\kappa)Q_t^{0*} + f(\sigma, \lambda, \Omega, [Q_1^{0*}, \ldots, Q_t^{0*}])$$

where λ translates merchantable timber volume into carbon stocks, and κ accounts for the proportion of these carbon stocks that are transferred to the pool of long-lived wood products. The first part of eq. 11 captures the direct emissions from timber harvests less the component of harvests stored in long-lived wood products. If the proportion of wood stored in long-lived products increases, the project benefits in terms of carbon saved will decline. The second part of eq. 11 accounts for the damaged and unused wood left on site. This wood material constitutes a stock of carbon residing in the forest slowly emitting carbon as the wood decomposes. The emission process is captured by the equation $f(\cdot)$, which is a function of σ, the proportion of damaged wood associated with timber harvests; Ω, the decomposition rate; λ (defined above); and cumulative harvests to time t. Following Brown et al. (2000*b*) (and an unpublished report to The Nature Conservancy[2]), we assume that λ equals 0.3 Mg C/m^3 (product of average wood density of harvested and damaged tree species (0.6 Mg/m^3) and the carbon content of biomass (0.5)), κ is 0.3 (from Winjum et al. 1998), σ is 3.0 (revised from Brown et al. 2000*b*), and Ω ranges from 7% to 12% per year (Brown 1987; Delaney et al. 1998). Cumulative, undiscounted carbon emissions are given as $C^{0*} = \sum_t C_t^{0*}$.

The carbon project removes several concessions from the timber supply base. The harvests associated with these concessions are given as $A = (A_1, A_2, \ldots, A_{T-1})$, and the cumulative carbon emissions are C^{A*}. These constitute the gross carbon savings associated with the NKCAP. With the removal of these concessions, a new path of timber harvests and carbon emissions is projected for Bolivia, accounting for adjustments in prices and management of the remaining timber and capital stocks. Timber harvests are given as $Q^{1*} = (Q_1^{1*}, Q_2^{1*}, \ldots, Q_{T-1}^{1*})$, and the cumulative carbon emissions are given as C^{1*}. The net carbon savings of the NKCAP is found as $C^{1*} - C^{0*}$. Carbon leakage is found as

$$[12] \quad L(\%) = 100[C^{A*} - (C^{1*} - C^{0*})]/C^{A*}$$

This measure of leakage assumes no discounting. Discounting can have two effects. First, the discounted carbon emission paths would be smaller than the undiscounted emissions paths, so the present value of carbon credits would be less than the cumulative undiscounted carbon credits. Second, discounting the carbon credits could alter the leakage estimates. Discounting can be easily incorporated by simply discounting the annual carbon emissions calculated above, as done below.

Leakage estimates

To estimate leakage, the Bolivian timber model is used to develop a baseline for timber harvests, and scenario analysis is used to test the effects of removing timber concessions from harvesting under several different assumptions. The supply of timber in Bolivia is derived primarily from five regions, (Table 1). Four of the regions — Santa Cruz, Beni, Pando, and La Paz — account for 84% of total harvests and 83% of total concession holdings. Cochabamba has few concessions, although it does account for 14% of total timber harvests. Harvesting intensity, as measured by harvests per hectare of concession holding, is highest in Beni because that region has fairly small concession areas, but the majority of these concessions are located close to La Paz and thus to Pacific Ocean transportation routes.

For the empirical analysis, the concessions located in the area indemnified by the NKCAP are modeled separately from the rest of the Santa Cruz region. The original area of the four concessions affected by the indemnification was ap-

[2] Winrock International 2002. 2001 Final report on leakage, baselines, and carbon benefits for the Noel Kempff Climate Action Project. Report prepared for Climate Change Initiative, The Nature Conservancy, Arlington, Va.

Table 2. Area of land in concession holdings in the area indemnified by the expansion of the Noel Kempff Mercado National Park.

	Concession			
	Paragua	El Chore	El Paso	Moira
Area before indemnification (1000 ha)*	464.5	224.1	371.1	512.4
Area affected by indemnification (1000 ha)*	73.5	140.7	214.9	232.7
Area in 1998 (1000 ha)†	112.9	0	0	0
Volume in area affected (1000 m^3)*	1496.3	3631.0	7124.1	1960.7
Volume of five export species (1000 m^3)*	687.1	1610.3	3148.5	1086.9

*Source: Mancilla (1999).
†Source: Superintendencia Forestal (2001).

proximately 1.5 × 10^6 ha before 1996 (Table 2). The report by Mancilla (1999) suggests that approximately 661 000 ha were indemnified by the concession agreements. Most of the land that was not indemnified was released from concession holdings subsequent to the implementation of the project. A portion in the Paragua concession remained under timber concession. This area is modeled as part of the overall area of land in concessions in Santa Cruz.

For modeling purposes, timber supply from nine regions is modeled in Bolivia. Four of the "regions" are the single concession holdings listed in Table 2. These concessions are separated out to account for more specific information on them available from Mancilla (1999). For the baseline, it is assumed that the 661 000 ha indemnified and the 112 900 ha now held by Paragua would have remained in concession holdings throughout the time period analyzed, because of the rich diversity of tropical timber available in that region (Mancilla 1999). Within the indemnified region, volumes of the five main export species range from 5 to 15 m^3/ha of land in concession (Table 2), with additional volumes of merchantable species for national markets ranging from 4 to 18 m^3/ha. The other five regions account for the remainder of concession and private landholdings in Bolivia: the rest of Santa Cruz, Beni, Cochabamba, Pando, and La Paz. Parameter values for transportation, milling, marketing, and other costs are obtained from Mancilla (1999).

Description of baseline cases

In this section, the assumptions relating to the scenarios under which leakage is estimated are described. The first set of assumptions address the possibility that sequestration programs may occur elsewhere and affect the prices Bolivian exporters receive for timber products sold abroad. Export prices are linked to the timber price paths described in Sohngen and Mendelsohn (2003), who explore a high- and a low-sequestration scenario. The low-sequestration scenario estimates worldwide sequestration of 13 × 10^9 t carbon by 2050 for \$30/t, while the high-sequestration scenario estimates that 34 × 10^9 t could be sequestered by 2050 for \$92/t. Under both the high and the low global sequestration assumptions, export timber prices are expected initially to increase relative to the baseline, but to fall below baseline prices in the longer term as global timber supply rises (Fig. 3). Domestic timber prices are determined endogenously by the model for each scenario. In the baseline, they are approximately \$372/m^3 initially, falling to \$215/m^3 by 2050. Note that although climate change could alter the productivity of Bolivian forests, and consequently timber supply, such changes in forest productivity are not considered here.

The second set of assumptions consider the availability of capital. As noted in Merry and Carter (2001), Bolivian timber markets are potentially capital constrained, so that even if domestic market prices rise, it may be difficult for concessionaires to increase their capital inputs to increase production. Two alternative constraints on capital adjustment are considered: unconstrained capital adjustment (UCAP) and constrained capital adjustment (CCAP). Under CCAP, capital investments in any particular year are constrained to be less than 5% of total capital in the industry. Timber harvests are larger under the UCAP assumption (Fig. 4), as the market operates with more capital overall. Figure 4 also shows historical harvests in Bolivia using two sources of data, FAOSTATS and local sources (J. Quispe and R. Vaca, Fundacion Amigos de la Naturaleza, 2002, personal communication), and harvests from the four concessions in Noel Kempff region under the CCAP assumption. The final set of assumptions explore an alternative demand elasticity. The baseline estimates assume that the price elasticity of internal demand is –1.3, following Merry and Carter (2001). This is reduced to –0.5 for the inelastic case.

Leakage is compared across eight alternative baseline scenarios. The first two scenarios are the baseline under UCAP and CCAP. The baseline assumes little to no forest sequestration in other regions of the world. Scenarios 3 and 4 are the low global sequestration program under UCAP and CCAP, while scenarios 5 and 6 are the high global sequestration program under UCAP and CCAP. Scenarios 7 and 8 are the inelastic-demand scenario, also under UCAP and CCAP. Cumulative timber harvests in the 661 000 ha of the NKCAP area for 30- and 50-year time periods for these eight scenarios are estimated and used to calculate both the cumulative and discounted cumulative carbon emissions (Table 3). These estimates reflect the total potential (gross) carbon savings from NKCAP without accounting for leakage.

The baseline estimates are generally consistent with historical timber trends in Bolivia and with historical harvesting intensity. Data from the time period 1996 to 2000 indicate that harvest intensities are 0.09 m^3/ha of concession land per year. The projected harvest intensity for the entire country is 0.09 m^3/ha between 1996 and 2000, rising to 0.23 m^3/ha by 2050. For the indemnified area, the harvest intensity is slightly higher, 0.13 m^3/ha per year between 1996 and 2000.

Leakage estimates

As shown in eqs. 11 and 12, the leakage percent is mea-

Fig. 4. Historical and projected national timber harvests in Bolivia, 1965–2050.

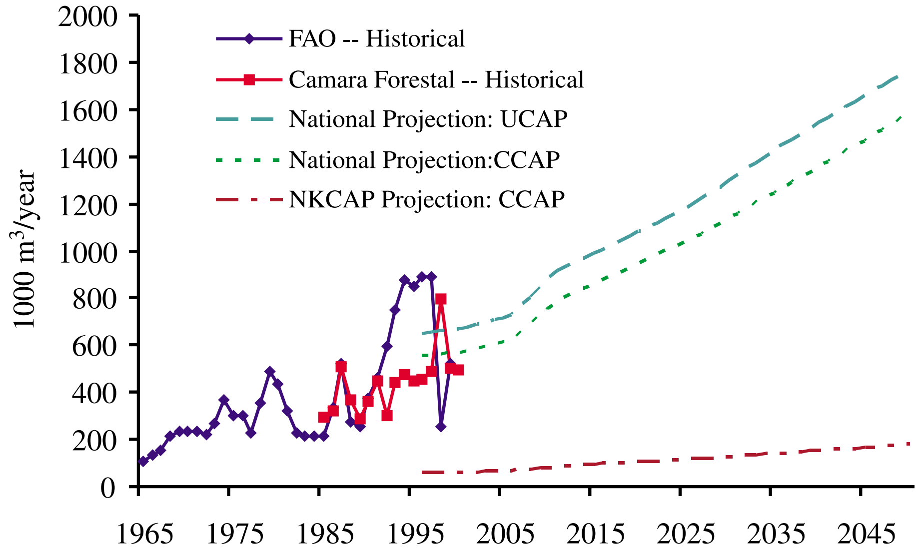


Table 3. Carbon emissions (10^6 t) from harvesting timber in the Noel Kempff Mercado Climate Action Project (gross potential carbon credit).

	Baseline		Low global sequestration		High global sequestration		Inelastic demand	
	UCAP	CCAP	UCAP	CCAP	UCAP	CCAP	UCAP	CCAP
30-year contracts								
7% decomposition rate								
Cumulative	2.01	1.68	2.00	1.67	2.01	1.68	2.09	1.79
Discounted present value*	1.20	1.00	1.20	1.00	1.20	1.01	1.25	1.08
12% decomposition rate								
Cumulative	2.07	1.72	2.06	1.72	2.07	1.73	2.15	1.84
Discounted present value*	1.20	1.00	1.20	1.00	1.20	1.01	1.25	1.08
50-year contracts								
7% decomposition rate								
Cumulative	4.91	4.15	4.91	4.12	4.92	4.10	4.66	4.23
Discounted present value*	2.10	1.76	2.10	1.76	2.10	1.76	2.06	1.83
12% decomposition rate								
Cumulative	5.00	4.23	4.99	4.20	5.01	4.18	4.73	4.31
Discounted present value*	2.10	1.76	2.10	1.76	2.10	1.76	2.06	1.83

Note: UCAP, unconstrained capital assumption; CCAP, constrained capital assumption.
*Carbon flows discounted at 3% per year.

sured by comparing the cumulative carbon flows (or the net present value of cumulative carbon flows) associated with the gross reduction in harvests caused by the set-aside to the cumulative carbon flows associated with the net reduction in national harvests. The leakage percentage is shown in Table 4 for the eight scenarios with and without discounting. (The net anticipated carbon credit for the project can be obtained by subtracting the leakage component from the gross component in Table 3.) For the 30-year time period and a decomposition rate of 7% per year, carbon leakage ranges from 18% in the constrained capital case to 24% in the unconstrained capital case. Leakage tends to be higher in the unconstrained capital case because other concessionaires can make investments rapidly in the short term to replace timber supply removed by the NKCAP project. For leakage measured over the longer 50-year time period, leakage is similar across the two capital scenarios, approximately 21% to 22%. Discounting reduces estimated leakage. For the 7% decomposition rate, leakage is approximately 3% lower with discounting, and for the 12% decomposition rate, leakage is approximately 37% lower.

Leakage tends to rise slightly if the rest of the world engages in carbon sequestration as well and export timber prices change. The effects are larger in the unconstrained capital case, although the effects of the global sequestration programs on the Bolivian project are not all that large for either case. As with the baseline case, capital constraints have important effects on leakage if it is measured over the shorter 30-year accounting time frame proposed originally for the NKCAP. Leakage estimates, however, are not heavily

Table 4. Estimated percentage of gross carbon emissions caused by leakage for alternative scenarios.

	Baseline		Low global sequestration		High global sequestration		Inelastic demand	
	UCAP	CCAP	UCAP	CCAP	UCAP	CCAP	UCAP	CCAP
30-year contracts								
7% decomposition rate								
Cumulative	23	18	23	18	24	18	35	39
Discounted present value*	22	18	22	18	22	18	34	38
12% decomposition rate								
Cumulative	11	5	11	5	12	5	24	29
Discounted present value*	6	2	6	2	7	2	21	26
50-year contracts								
7% decomposition rate								
Cumulative	22	21	22	21	23	21	31	42
Discounted present value*	12	12	13	12	14	12	23	36
12% decomposition rate								
Cumulative	21	20	22	20	23	20	32	41
Discounted present value*	9	7	9	7	10	7	21	32

Note: UCAP, unconstrained capital assumption; CCAP, constrained capital assumption.
*Carbon flows discounted at 3% per year.

affected by capital constraints for the longer 50-year accounting time frame shown.

The results highlight the importance of the rate of decomposition of deadwood (logging slash and damaged trees) in the forest. The two decomposition rates considered for this study (7% and 12% per year) are estimated to represent the minimum and maximum rates (Brown 1987; Delaney et al. 1998). Carbon leakage is substantially lower with faster decomposition rates. Faster decomposition (modeled as a function of the stock and decomposition rate) actually leads to smaller annual emissions from dead material because the overall stock of dead material is smaller. In general, if less dead and decaying material is produced in areas to which timber harvests “leak” than in the area where harvests are eliminated, carbon leakage will be smaller. Thus, avoiding harvests in a tropical region, where relatively high damage occurs with each log removed, and shifting these harvests into regions where there is slightly less damage will reduce leakage. Most of the leakage in this study occurs in other areas of the Santa Cruz Department, or in regions with similar or more intensive harvests, and hence similar, or smaller, logging damages.

As expected, leakage rises in the scenario where the internal demand for Bolivian timber products is assumed to be more inelastic. In the UCAP scenarios, leakage rises to 24%–35% over the 30-year period, depending on decomposition rates for damaged forests, and 23%–31% over the 50-year period. In the CCAP scenarios, leakage ranges from 29% to 39% in the 30-year period and from 36% to 42% in the 50-year period. Net carbon credits are definitely reduced if demand is more inelastic, suggesting that leakage will be greater in regions where local markets rely heavily on locally produced forest products.

Discussion and conclusion

This study investigates the potential leakage arising from carbon projects on timberland in an open economy. Specifically, we explore a set-aside whereby concessions in Bolivia are removed from the harvesting base for that country. The analysis is based on the Noel Kempff Climate Action Project undertaken by The Nature Conservancy and local partners in Bolivia. This project sets aside approximately 661 000 ha of land, of which approximately 79% is productive forestland. To estimate leakage, a model of Bolivian timber markets was developed to project a baseline timber harvest within the country and within the project area. Markets were assumed to respond to a perfectly elastic export demand function, but a downward sloping domestic demand function. Sensitivity analysis was conducted to determine how baseline and leakage estimates are potentially affected by alternative assumptions about worldwide sequestration efforts, by alternative assumptions about the availability of capital for timber production in Bolivia, by alternative assumptions about the elasticity of the domestic demand function, and by alternative assumptions about the decomposition of logging slash and damaged trees.

The results suggest that leakage could range from as low as 5% to as high as 39% within the 30-year period of the original project. Leakage estimates are sensitive to all of the factors explored in this study; however, the decomposition rate of dead material and demand elasticity appear to have the largest effect on leakage. The effects of the capital constraints have important implications for net carbon gains only if the project period is short. Bolivia is an economy with constrained capital because of a recent banking crisis, so the lower estimates of 18% (30-year project) to 21% (50-year project) leakage are likely more appropriate for that country. Countries with greater access to capital markets and internal banking infrastructure for distributing that capital are likely to have larger leakage.

In comparing these results with those of others, our projected net reductions in timber harvests are larger than estimates derived from the study by Merry and Carter (2001). One reason is that the present study incorporates region-specific information, whereas the Merry and Carter study is carried out with national-level statistics. Another reason is that this study analyzes the period following a change in timber law in 1996, when harvest intensities on areas held in concessions rose from less than 0.02 m^3/ha of concession land to more than 0.09 m^3/ha of concession land. A study by Murray et al. (2004) projects that mature forest set-asides in the United States ranging from 40 485 ha in the Pacific Northwest region to 267 000 ha in the South Central region would lead to carbon leakage of 16.2% to 68.3%, respectively. The lower end of their spectrum is well within the range of leakage estimated in the present study, although the higher end is clearly much larger. Their leakage estimates likely should be larger. First, they measure leakage for the entire United States, a much larger country than Bolivia. Second, there is better access to capital markets, which suggest overall larger leakage. In Bolivia, new roads must be built to access forests, and wood must be transported long distances to markets, thus reducing potential leakage in Bolivia relative to the United States.

As found in this study and others, leakage is an important issue for carbon sequestration projects to consider; however, it does not necessarily make a project unattractive. Primary leakage, as discussed above, can be controlled with contractual instruments that remove processing equipment and individual entrepreneurs from the industry. Secondary leakage cannot be as easily controlled, but can be measured and incorporated into the relevant carbon accounting framework, as shown in this paper. Individual projects may also be able to take advantage of potential synergistic effects by including multiple components. For example, by indemnifying timber concessions and protecting land by placing it in reserved status (i.e., national parks), the overall NKCAP project is estimated also to reduce carbon emissions by avoiding deforestation (Aukland et al. 2003).

Although this study provides an indication about potential leakage, one important limitation that should be addressed through future research is the project baseline. The present paper controls for alternative baselines through sensitivity analysis, and although the results are not highly sensitive to the price effects in the low and high global sequestration scenarios, Bolivian or global market conditions could change for many different reasons. It is unclear whether overall market forces would tend to increase or reduce baseline-projected harvests, so project partners should continue to assess the potential baseline over time. Reexamining the baseline is also important because the results in this paper imply that the project continues providing benefits beyond the original 30-year period (i.e., the cumulative and discounted values of the 50-year project are larger than those of the 30-year project). Thus, depending on market conditions, there could be substantial value remaining in the project at the time the original contract matures.

Acknowledgments

This work was funded by The Nature Conservancy (Contract No. AO22797) to Winrock International, Sandra Brown, Principal Investigator. We thank our colleagues who provided insights and information to this work, namely Richard Vaca, Jaime Quispe, Louise Aukland, and Bill Stanley.

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