

Forest transition in Vietnam and displacement of deforestation abroad

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Edited by B. L. Turner II, Arizona State University, Tempe, AZ, and approved July 27, 2009 (received for review May 8, 2009)

In some countries across the globe, tropical forest cover is increasing. The national-scale reforestation of Vietnam since 1992 is assumed to contribute to this recovery. It is achieved, however, by the displacement of forest extraction to other countries on the order of 49 (34–70) M m³, or ≈39% of the regrowth of Vietnam's forests from 1987 to 2006. Approximately half of wood imports to Vietnam during this period were illegal. Leakage due to policies restricting forest exploitation and displacement due to growing domestic consumption and exports contributed respectively to an estimated 58% and 42% of total displacement. Exports of wood products from Vietnam also grew rapidly, amounting to 84% of the displacement, which is a remarkable feature of the forest transition in Vietnam. Attribution of the displacement and corresponding forest extraction to Vietnam, the source countries or the final consumers is thus debatable. Sixty-one percent of the regrowth in Vietnam was, thus, not associated with displacement abroad. Policies allocating credits to countries for reducing deforestation and forest degradation should monitor illegal timber trade and take into account the policy-induced leakage of wood extraction to other countries.

leakage | reducing emissions from deforestation and forest degradation | reforestation | illegal timber trade | forestry policies

There are signs of tropical forest recovery in a few countries (1–3), but its causes and implications remain inadequately understood, especially with respect to international agendas that would provide carbon credits for tropical forest protection (4, 5).

Vietnam underwent a forest transition—i.e., a national-scale shift from net deforestation to net reforestation—in the early 1990s (6). Forest cover has grown steadily since that time, from 24.7 (24.6–31.1)% of the country's area in 1992 to 38.2 (34.4–42.1)% in 2005. Several internal political, socioeconomic, and land-use processes contributed to this reforestation (7). During this period, logging was severely restricted in natural forests by successive forestry policies, whereas recorded wood imports have increased substantially and large quantities of illegal logs entered the country, mostly from Cambodia (8) and Laos (9). At the same time, Vietnam banned the exports of raw logs and developed a flourishing furniture manufacture and export sector (8, 10). This suggests that Vietnam protected its forests and developed its economy by exporting its deforestation to neighboring countries, a situation considered as leakage by various forest conservation programs.

Leakage—an increase in deforestation/degradation [or greenhouse gases (GHG) emissions] somewhere caused by the reduction of deforestation/degradation (or GHG emissions) elsewhere—is a major challenge in policies aimed at protecting forests and mitigating carbon emissions. Leakage has been studied mainly through spatially explicit assessments of local spillover around protected areas (11, 12) or through econometric modeling at local (13) or country to global scales (14), with mixed evidence. Local studies account mainly for primary leakages, i.e., leakages caused by the same agents that are responsible for the targeted activities (15). Leakage calculated by large-scale econometric models represent from 42% to 95% of the reduction of deforestation implemented by a country (14). These models

usually account for primary and secondary leakages, the latter being the leakage due to incentives such as increasing prices generated by protection measures (15).

Background

The forestry sector in Vietnam is represented in Fig. 1. Industrial roundwood extracted from natural and planted forests of Vietnam constitutes the domestic supply. When added to legal and illegal roundwood imports, it constitutes the total industrial roundwood supply. Part of it may be exported as roundwood, and the rest is processed in the country to produce sawnwood, plywood, chips, and other intermediate products. Some processed wood is also imported. This pool is then transformed into secondary processed (or value-added) wood products (SPWP) such as furniture, joinery, or construction wood, for either domestic use or export. When added to exports of roundwood and processed wood, they constitute the total wood consumption and exports of the country. The annual increase in commercially exploitable growing stock volume in the forests—called the annual increment—is due to the growth of existing trees, natural regeneration of forests on abandoned land, and afforestation and reforestation.

Displacement, a more general concept than leakage, is defined as a temporal, spatial, social or sectoral separation between consumption and production of a material good (16), in this case wood products. Displacement from one country to another of wood extraction and its ecological impacts is not exclusively the result of reforestation in the first country, because it accounts for any flow of wood that is used domestically but extracted abroad. In the context of Vietnam, total displacement should be separated into policy-induced leakage and demand-driven displacement. The former occurs when an increase in displacement of wood extraction is due to a policy-induced reduction in domestic roundwood supply, with unchanged consumption of SPWP and exports. Policy-induced leakage is the focus of most studies (11, 13, 14, 17). The latter occurs when an increase in displacement abroad is due to an increase in domestic consumption and exports of SPWP that remains unmatched by a corresponding increase in domestic supply, assuming unchanged policies.

The objective of this study is to address two related questions: (i) Is the forest transition in Vietnam associated with a leakage of forest extraction outside its borders? (ii) If all of the timber imported by Vietnam from foreign countries between 1987 and 2006 had been extracted from Vietnamese forests, how would these forests growing stock, area, and quality have changed? The study period spans the 5 y before the forest transition, the turning point in forest cover, and the following 15 y of net reforestation. We use a material flows analysis to estimate the displacement of

Author contributions: P.M. and E.F.L. designed research; P.M. performed research; P.M. and E.F.L. analyzed data; and P.M. and E.F.L. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

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This article contains supporting information online at www.pnas.org/cgi/content/full/0904942106/DCSupplemental.

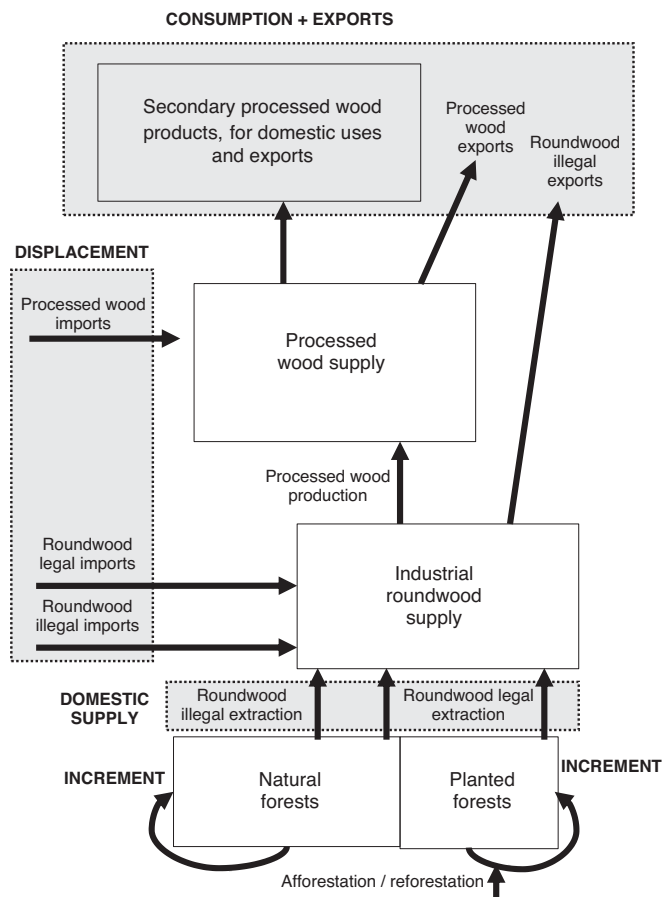


Fig. 1. Flowchart of the forestry sector in Vietnam.

forest exploitation to neighboring countries generated by Vietnam, separating it into its policy-induced and demand-driven components. This approach is similar to that used in demography to analyze population dynamics by separating it into the rates of different components of change (18). The displacement is then compared with the exports generated from Vietnam and to the unexploited annual increment in wood volume produced by forests in Vietnam. We evaluate the consequence of the displacement for the changes in density, area, and quality of forests in Vietnam. Time series of domestic wood extraction, processing, legal imports, and exports were obtained from FAO, and converted to roundwood equivalent (RWE) volume. Illegal timber imports for 1997–2006 were calculated as the gap between domestic supply plus legal imports of roundwood and production of processed wood products, and for 1987–1997 based on an extrapolation of published figures. Policy-induced leakage was calculated as the fraction of displacement that would have been extracted in domestic natural forests absent any reduction in harvest quotas in these forests, based on an extrapolation of wood extraction before this policy following the evolution of wood prices. The residual part of total displacement constituted the demand-driven displacement. The annual increment in commercially exploitable (i.e., wood for industry, construction, and pulping) growing stock in forests was estimated by using forest cover area data from the Vietnamese Forest Inventory and Planning Institute (FIPI) and parameters from the literature.

Results

Total domestic supply of roundwood in Vietnam was stable throughout the period from 1987 to 2006, ranging between 3.5 and 5.4 M m³ per year [Fig. 2A and supporting information (SI

Table S1]. Illegal extraction in the country doubled during the period but remained a small share of total roundwood production. Industrial demand, however, grew dramatically, with a rapid increase in production and exports of processed wood and SPWP (Fig. 2B and C) and in imports of processed wood (Fig. 2D). Legal imports of roundwood did not increase sufficiently to feed the growth in the Vietnamese processing industry, given restrictions on timber exports in neighboring countries, resulting in an increasing gap between consumption and legal roundwood imports. This gap was filled with illegal imports (Fig. 2E) that represented ≈48.1% of the total volume of imports. Over the 20 y, total imports and exports represented, respectively, 40.8 and 34.4 M m³.

Total displacement, expressed in volume extracted or destroyed in forests abroad, was null at the beginning of the period, then ranged between 2.4 and 4.6 M m³ per year between 1998 and 2003 and then grew rapidly to reach 10.2 M m³ in 2006 (Fig. 2F, Table 1, and Table S2). From 1987 to 2006, policy-induced leakage and demand-driven displacement represented respectively 58.0% and 42.0% of the total displacement (Table 1 and Fig. 2G).

The annual increment of commercially exploitable wood in the forests of Vietnam increased linearly during the 20 y due mainly to the maturation of plantations and the continuing afforestation and reforestation (Fig. 2H–J). Because roundwood extraction remained stable during the period, the unharvested fraction of the annual increment followed the same increasing trend as the total increment. This fraction was close to zero in the beginning of the period, and increased to 6.9 M m³ in 1998 and 13.6 M m³ in 2006. For the 20 y, the total displacement represented an estimated 39.1% of the unexploited wood increment in Vietnamese forests.

The final figure of displacement, with its low and high estimates, is an annual average of 2.5 (1.7–3.5) M m³ y⁻¹ and a total of 49.0 (33.9–69.6) M m³ for the period (Tables S2 and S3). Uncertainties are higher for the unexploited increment of wood volume, with a figure of annual average of 6.3 m³ y⁻¹ with low and high estimates of 3.1 and 10.2 M m³ y⁻¹ (Table S3). These figures cumulate the low and high values of all parameters that respectively decrease and increase estimates. The largest uncertainties are in forest area (6). Because actual biases are unlikely to be all in the same direction, these low and high estimates are extreme boundaries. The range of realistic values is probably much narrower (SI Text).

Discussion

Forestry Policies and the Wood Sector. Dramatic changes have occurred in wood production and trade in Vietnam over the last 20 y (Figs. 1 and 2). Throughout the 1990s, the government shifted the source of wood from natural forests toward plantation and imports (Fig. 2G) and shifted the exports from raw wood toward value-added processed wood (Fig. 2C). In 1992, harvesting quotas in natural forests were strongly reduced (19), and exports of raw cut and sawn wood were banned. In 1993, logging was banned on all “special-use” forests (protected areas and reserves) and on all natural forests in the northern provinces, and a 30-year moratorium was imposed on logging in important watershed areas (20). In 1998, the ban on commercial logging in natural forests was extended to the whole northern highlands, the southeast, and the Mekong River and Red River Delta provinces, representing 58% of natural forests (21). Extraction quotas for large-diameter logs in natural forests decreased from 1.2 M m³ in 1992 to 300,000 m³ per year since 1998 (21), and 250,000 m³ per year after 2003 (22). During the early 1990s, the growth of the wood industry supplied mostly the increasing domestic demand, associated with the construction boom and rapid economic growth that followed economic and political reforms (23, 24) (Fig. 2K). In the 2000s, the wood processing

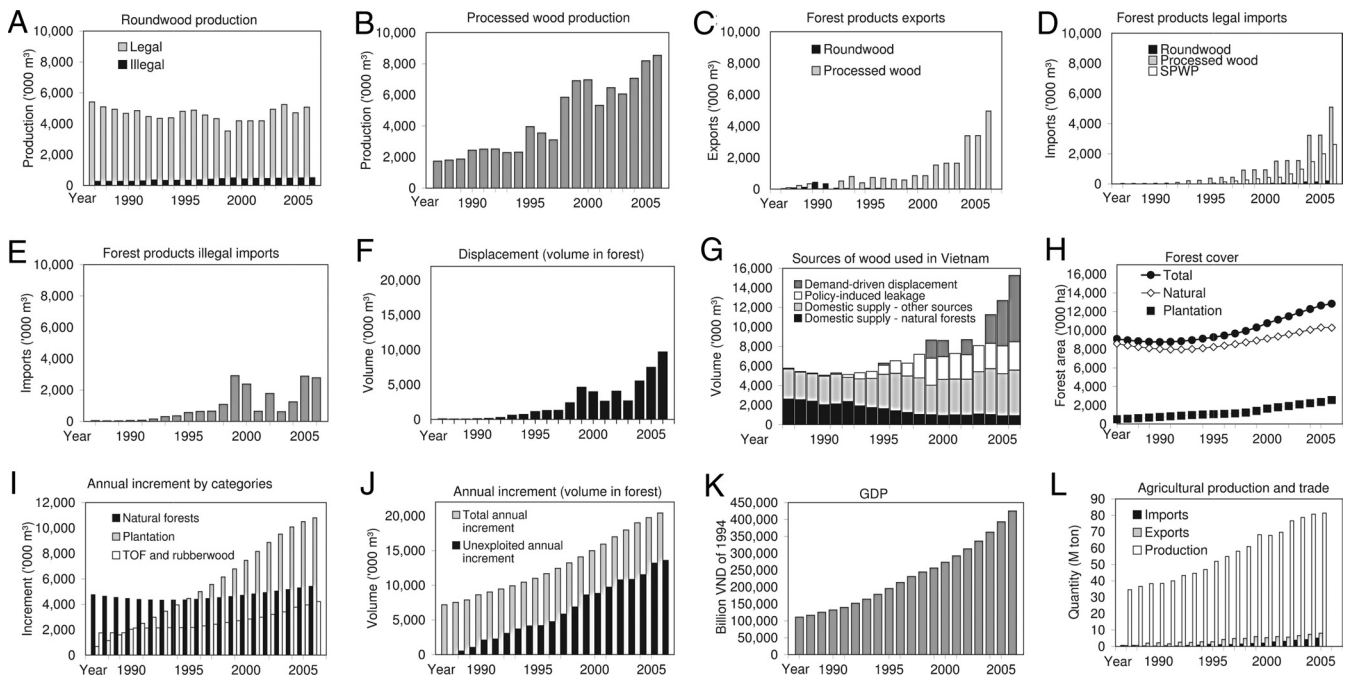


Fig. 2. Wood flows and other forest-related indicators in Vietnam, 1987–2006. Displacement and annual increment are in volume in forest (RWE volume \times 1.2), other wood quantities are in RWE volume. (A) Domestic industrial roundwood production (legal and illegal). (B) Processed wood production. (C) Forest products exports (roundwood, processed wood, and SPWP). (D) Forest products legal imports (roundwood and processed wood). (E) Forest products illegal imports. (F) Displacement of wood extraction into foreign countries. (G) Sources of wood used in Vietnam, 1987–2006. Harvests from natural forests and from other sources (forest plantations, scattered trees, rubberwood) form the domestic supply. Policy-induced leakage and demand-driven displacement form the total displacement. (H) Forest cover (natural and plantations). (I) Annual increment in wood volume per sources. (J) Annual increment in commercially exploitable growing stock in Vietnam’s forests, total and unexploited fraction. (K) Gross domestic product (GDP) in constant Vietnam Dong of 1994 from www.econstats.com. (L) Total production and trade (imports and exports) of agricultural products from FAOSTAT (faostat.fao.org). Production include only primary (nontransformed) crops.

industry became increasingly export oriented and, especially after 2003, furniture exports became important sources of wood consumption and foreign currency earnings.

Because, despite the growth in illegal logging, the domestic supply of roundwood was insufficient to feed the growing processing industry, and as neighboring countries also imple-

mented bans on raw wood exports, the raw material was increasingly supplied by illegal imports from other countries—Cambodia and Laos in the early 1990s and then also Malaysia, Myanmar, and Indonesia (Fig. 2E). Despite this, an exponential increase in processed wood imports—mainly pulp, paper, boards, and sawnwood from various countries, including Malay-

Table 1. Summary of displacement, leakage, and wood regrowth in Vietnam’s forests, 1987–2006

Parameter	Total (M m^3)	Percentage of total regrowth	Percentage of displacement
Total regrowth (unharvested increment in growing stock)	125.4	100.0	—
Of which:			
Not discounted by displacement	76.4	60.9	—
Discounted by displacement	49.0	39.1	100.0
Separated into:			
Policy-induced leakage	28.4	22.7	58.0
Demand-driven displacement	20.6	16.4	42.0
Corresponding to:			
Exports	41.3	32.9	84.3
Consumed domestically	7.7	6.1	15.7
Separated into:			
Illegal imports	19.9	18.8	48.1
Pulp, paper, and chips legal imports	13.5	12.9	33.1
Other legal imports	8.0	7.4	18.8

All data in volume in forest (RWE volume \times 1.2), except imports values (first column of the three last rows), which have to be multiplied by 1.2 to account for logging wastes, in order to obtain values of displacement. Illegal imports are mostly roundwood from natural forests. Pulp, paper and chips legal imports come mostly from plantations. Other legal imports are mostly other processed wood.

sia, China, and Indonesia—was necessary to feed the domestic consumption and exports of wood products (Fig. 2D). Increases in imports of both illegal roundwood and legal processed wood resulted in an ever-growing displacement of forest exploitation abroad (Fig. 2F).

Policy-Induced Leakage and Demand-Driven Displacement. Was forest recovery made possible in Vietnam by shifting pressure on forests in foreign countries? Before the forest transition, in 1987, the sum of consumption and exports was equal to domestic supply in Vietnam. During the following 20 y, the total domestic supply was stable (Fig. 2D and G). Forest protection policies caused a reduction in harvests from natural forests and an increase in harvests from a growing area of plantations and in wood imports. Thus, shifts in wood extraction pressure occurred, from natural to planted forests and from domestic forests to forests abroad. Without the policy shifts noted, presumably, the increasing consumption and exports in Vietnam would have been at least partly supplied by greater harvests in domestic natural forests, because it would have been the cheapest way to obtain roundwood.

The major cause of displacement changed during the 20 y. From 1987 to 2003, displacement abroad was mainly due to the new state policies (Fig. 2G). In their absence, domestic sources would have produced $\approx 76.5\%$ of the volume of wood that has been obtained from abroad. This estimate is high because it assumes that, without policies, extraction would have continued unabated. In reality, in the north of Vietnam mainly, many forest enterprises ceased their activities or suffered financially in the 1990s, not because of forest policies but because of a growing scarcity of raw material (25, 26). Before the logging and export bans, harvests from natural forests were declining in Vietnam. From 2004 to 2006, the dramatic increase in displacement was associated with a rise in domestic consumption and exports. Forest policies were broadly unchanged, and most of the displacement for this period— 63.4% —was demand driven (Fig. 2G). Even with less-stringent forest exploitation regulations, the demand could not have been fully supplied domestically.

The growth of Vietnamese exports in wood products—mostly semifinished or finished products—was a major source of wood demand and, thus, of displacement and is a remarkable feature of the forest transition in Vietnam. Expressed in volume cut in forests, exports represented 84% of the displacement. Their processing in Vietnam provided important benefits to the economy. But exports from Vietnam could be removed or at least separated in the displacement analysis because they were not consumed in the country. Subtracting exports, total displacement for the 20 y drops to only 7.7 M m^3 , or 6.1% of the regrowth in Vietnamese forests. Regarding wood products exported from Vietnam, the attribution of the responsibility of the displacement is debatable. It is shared between the country consuming Vietnamese products, Vietnam that imports illegal timber, and the source countries where illegal harvesters often collude with officials (8, 10).

Food imports to Vietnam could also produce a displacement abroad of the agricultural production and associated deforestation. In reality, since 1989, agricultural production in Vietnam has steadily increased (Fig. 2L). Imports to Vietnam have also increased, but exports from Vietnam have been much higher for all years, and both are of a lower order of magnitude than agricultural production. Displacement of deforestation due to food imports was thus negligible.

Displacement and Forest Changes. If all timber imported by Vietnam had been extracted from Vietnamese forests, would it still have been possible to increase the forest growing stock and area while not further decreasing the quality of forests in Vietnam? This possibility is plausible because the main taxa imported

illegally are indigenous to Vietnam (10). For the 20 y from 1987 to 2006, $\approx 39.1\%$ of the wood increment that actually took place in Vietnamese forests should have been extracted to replace all imports, all other things being equal. A maximum of 22.7% of the regrowth would not have taken place without the forest protection policies (i.e., 58.0% of the 39.1%), and $\approx 16.4\%$ of the regrowth would not have taken place without the economic growth (i.e., 42.0% of the 39.1%). During recent years, with the dramatic increase in exports of wood products, the ratio of displacement on forest regrowth increased. In 2006, 71.4% of the forest regrowth in volume would not have taken place if the wood supply in Vietnam had been entirely domestic. If exports are removed, only 6.1% of the regrowth should have been extracted to supply the domestic consumption without imports.

Compared with the regrowth in wood volume, the increase in forest area depended less on a displacement of wood extraction abroad, because it was mainly associated with land allocation policies and agricultural changes (7). Some forest area increase would still have taken place since 1992 without displacement of wood extraction abroad.

There has been, however, a shift in the types of wood produced and in forest quality in Vietnam. In 1987, Vietnamese old growth forests provided many large-diameter logs of high-quality wood. In the 2000s, Vietnamese plantations provided mainly small-diameter logs and low-quality wood not suitable for all sectors (27). The growing furniture industry, notably, uses a large volume of high-quality wood. It thus generates a demand for high-value logs from primary forests, which are often traded illegally. Restrictions in harvests and the consequent displacement abroad relieved some of the pressure on the few remaining primary forests in Vietnam and their rich biodiversity, but the reforestation had few benefits for the quality of Vietnam's forest. Although forest area and volume have steadily increased during the last 15 y, the degradation of primary forests continues. The secondary regrowths have a low density and a poor biodiversity. Monocultures of fast-growing exotic species make approximately half of the forest area increase in Vietnam.

All of the displacement of forest extraction outside Vietnam for imports of processed wood did not necessarily result in deforestation or forest degradation abroad, because it may have come in part from plantations or well managed forests. However, illegal imports of natural timber, representing approximately half of wood imports, resulted in deforestation and forest degradation in the source countries (8).

Displacement in Theories of Land and Forest Cover Change. Beyond the implications for Vietnam, this case informs themes and theories of land change and the forest transition. Displacement may have a positive environmental impact globally if imports of forestry (or agricultural) products to a country come from a place with more productive land and/or more efficient production systems. A more optimal adjustment of land uses to the capacity of land and concurrent land-use intensification is one of the basic mechanisms of forest recovery at a national scale (28). A more intensive land use concentrated on a smaller area may also reconcile raw material production with environmental conservation at the global scale (29). But as for agriculture, the spatial concentration of forestry at the international scale is guided not only by the land productivity potential but also by land and labor costs, political stability (30), and environmental/resource governance. Although the theory of an adjustment of land use that optimizes land potential is relevant to understand land use changes within countries (28, 31) and at the local scale in Vietnam (7); it cannot be applied to the regional or global scales without further examination. Furthermore, the associated increase in transportation produces its own environmental impacts, and the land released by such land-use adjustment and intensification does not always return to a forested state (32).

Although the importance of international trade and colonial relations were recognized early in forest transition theories (33), quantitative analyses have mainly focused on the local or national scales (34, 35). This study showed that the displacement associated with national-scale forest recovery should be measured and its components attributed to forest policies and economic growth of the forestry sector. Similar processes happen in other countries such as China, where displacement, exports, and forest recovery are also interlinked (36). Current theories of forest recovery at a national scale should be refined to account for displacement and leakage between countries after globalization (37). Recent forest resurgence in several Latin American countries was partly driven by replacement of domestic agricultural production by imports and by foreign subsidies, another form of displacement (38, 30). In line with theories of the ecological modernization (35), displacement might constitute a temporary necessity: initial forest protection policies and increasing demand from economic development generate displacement, whereas domestic supply lags behind, especially with the long rotation time in forestry. Then, thanks to forestry and agricultural intensification induced by the increasing demand, domestic supply progressively catches up with consumption. The current trends in Vietnam do not suggest that supply will meet the rapidly growing demand anytime soon because, over recent years, self-sufficiency in wood declined (Fig. 2*G*).

Relevance for Reducing Emissions from Deforestation and Forest Degradation (REDD) Policies. Reducing forest degradation and loss are cost-effective ways to decrease carbon emissions (4). The recent political negotiations under the United Nations Framework Convention on Climate Change (UNFCCC) about REDD proposes to enhance this mechanism by allocating carbon credits to countries that decrease their rate of deforestation or forest degradation. REDD and other such schemes highlight the necessity to understand, quantify and reduce leakage to be effective at a global scale (14, 39). In the case of Vietnam, during the 1987–2006 period, leakage of forest extraction abroad due to policies protecting domestic forests represented $\approx 23\%$ of the volume of regrowth in Vietnam's forests. National-scale accounts of leakage, the participation of the largest number of countries in the REDD scheme, and combined or differentiated incentives for countries with high and low deforestation and forest cover levels are the most effective ways to address leakage inside countries and preserve the global additionality of the policies (5). However, leakage remains an issue in the implementation of forest protection policies, especially when it is due to illegal trade. Illegal logging is a major source of degradation of high-quality forests. Furthermore, when a displacement of wood extraction mostly feeds exports of value-added products, the attribution of responsibility to deforestation or forest degradation (if it indeed occurs) is debatable. Such questions would also arise if a REDD scheme would account for carbon stocks in wood products such as furniture. The case of Vietnam also shows that, in policies like REDD, forest degradation is as critical as deforestation (40).

Conclusion

Forest recovery in Vietnam during the last 20 y has been rapid. Yet, it was not only the results of domestic efforts but also of the displacement of wood extraction to neighboring countries. The equivalent of 39.1% of the volume of wood regrowth that took place in Vietnam's forests has been extracted from forests abroad to supply Vietnam's needs.

The leakage due to policies restricting harvests in natural forests and displacement due to the growing wood consumption and exports represented, respectively, 22.7% and 16.4% of the increase in growing stock of Vietnam's forests. Without the rapid increase in fast-growing wood plantations in Vietnam that

stabilized the domestic supply, total displacement would have been greater. The growth of the wood processing industry, large programs of plantations, and natural forest protection were all part of the same national forest strategy. In the case of Vietnam, displacement, exports, and forest transition are thus interlinked. When policies—such as may be implemented through a REDD scheme—aimed at protecting forests lead to a decrease in harvests without accompanying measures to control wood consumption and/or increase wood production from plantations and processing efficiency, then leakage abroad will most likely occur. Leakage should thus be directly addressed in forest protection policies. Illegal trade flows contributed to 48.1% of the displacement of wood extraction generated abroad by Vietnam. The exports from Vietnam represented $\approx 84\%$ of the imports. Attribution of the displacement and corresponding forest extraction to Vietnam, the source countries or the final consumers is thus debatable. Such an increase in exports of wood products is uncommon for places undergoing a forest transition. Yet, $\approx 60.9\%$ of the regrowth that actually took place in Vietnam's forests can be considered as free of displacement. This constitutes a net gain for the world's forests and carbon sink.

Materials and Methods

Data. Data about legal flows of agricultural products, wood, and wood products imports, exports, and production in Vietnam from 1987 to 2006 were taken from the Food and Agriculture Organization of the United Nations (FAOSTAT) database (faostat.fao.org). Figures of illegal domestic wood extraction for commercial and smallholder uses, and of illegal imports of timber for 1997 were taken from ref. 25, the only study that compiled several estimates of illegal wood cutting and imports in Vietnam as reported by NGOs, external consultants, and official records. These estimates were based on an extrapolation of field observations at major crossing points between Cambodia and Vietnam, wood flow analyses in Vietnam and in source countries, and other accounting methods. These three variables were extrapolated to the other years based on a fixed relationship with, respectively, wood prices on the domestic market, rural population density, and the quantity of legal imports of wood (*SI Text*). SPWP exports were obtained from ref. 25 and the United Nations COMTRADE database (comtrade.un.org). We used spline interpolation of data on forest area and types for the years 1980, 1992, 1995, and 2005 from the FIPI (6). Volumes of commercially exploitable wood from "Trees Outside Forests" (TOF, called scattered trees in Vietnam) and rubberwood were reconstructed from various sources (*SI Text*).

Methods. The first step was to estimate flows of wood and wood products from foreign countries to Vietnam, especially illegal timber trade. Discrepancies between domestic production, legal imports and consumption of forest products may be used to estimate illegal timber trade (41). All FAO data were converted to RWE volume (Table S4). These conversion factors were assumed to be constant throughout the period, because gains in processing efficiency were compensated by the decrease in the diameter of logs due to the depletion of natural forests and the increased reliance on fast-growing plantations (42). Legal imports of industrial roundwood and processed wood were drawn from FAOSTAT data (Fig. 1, Eq. 1). Illegal imports were estimated as the difference between, on the one hand, the quantity of RWE processed in the Vietnamese industrial sector or exported as roundwood and, on the other hand, the quantity of RWE extracted legally and illegally from Vietnamese forests for industrial purposes plus legal imports of roundwood (Fig. 1, Eq. 1) (41). This assumes that all illegally imported logs enter the legal processing industry—encouraged by fiscal policies—and that illegal imports of processed wood products are negligible, as shown by ref. 8, 10, 43. The balance of inputs and outputs in Vietnam's wood processing sector is:

$$PRw + IRwL + PRwIII + IRwIII = PPr + ERw \quad [1]$$

where PRw is the legal (recorded) production of roundwood (including sawn-logs and veneerlogs, pulpwood, and other industrial roundwood); $IRwL$ are the legal imports of industrial roundwood; $PRwIII$ is the domestic illegal extraction of commercial roundwood; $IRwIII$ are the illegal imports of roundwood (the unknown variable); PPr is the production of processed wood products, and ERw are the legal exports of roundwood. For the period 1987–1997, inaccuracies in the FAO data prohibited the calculation of illegal imports by the input–output balance method (*SI Text*). Instead, the available estimate of illegal imports for 1997 (25) was used and extrapolated to previous

years (*SI Text*). The total volume of wood products imported to Vietnam was calculated as the sum of legal imports of roundwood and processed wood products, and of illegal imports of wood. To account for the residues and wastes from logging, displacement—which corresponds to the volume of commercially exploitable wood cut in forests outside Vietnam—was assumed to represent 120% of the total volume of wood imported (44). Total exports were calculated as the sum of exports of roundwood, processed wood and SPWP (furniture) (*SI Text*).

In the second step, policy-induced leakage and demand-driven displacement were estimated. Until 1991, the forestry policy did not restrict harvests. All of the displacement was therefore considered as demand driven. Policy-induced leakage since 1992—the year of the first export ban and harvesting quotas—was calculated as the difference between harvest in natural forests that would have taken place absent any forest protection policy and harvest in natural forests that actually took place. The former was estimated by extrapolating the harvest from natural forests in 1991 according to a linear relationship with wood prices.

This assumes that extraction costs would have remained constant, because technological progress was compensated by the depletion of accessible and exploitable natural forests. Prices were assumed to be unaffected by changes in domestic supply because: (i) despite logging restrictions, total domestic supply did not decrease thanks to new plantations (Fig. 2 A and I), (ii) the log export ban reduced domestic roundwood prices and thus counteracted the price impact of the logging ban (45), and (iii) supply from abroad was abundant and cheap. Demand-driven displacement after 1991 was calculated as the difference between total displacement and policy-induced leakage. These estimates of policy-induced leakage and demand-driven displacement may miss some of the inter-annual variability, e.g., because of accidental factors that affect the quantity of

wood harvested in a particular year. Thus, although these figures should not be interpreted for a specific year, they reveal decadal-scale trends.

The third step was to compare annually the displacement to the increment in commercially harvestable growing stock in Vietnam's forests. Values of mean annual increment (MAI) in commercial growing stock were estimated by using published figures for Vietnam (44): respectively, 0.75, 0.575 and 0.4 m³ ha⁻¹ y⁻¹ for rich, medium and poor forests as classified in FIPI data; and 10 m³ ha⁻¹ y⁻¹ for plantation forests (given the species planted in Vietnam, *SI Text*). Plantation forests area increased continuously during the period, from 200,000 ha in 1980 to 2.3 M ha in 2005 (6) (Fig. 2H). Using total plantation area in 1 y to estimate increment in harvestable growing stock during this year would therefore merge mature plantations with young plantations not yet exploitable. Using a rotation time of 10 y for most of the plantations in Vietnam (22), we calculated the annual wood increment from plantations in 1 y by using the plantation forests area 10 y before. Volumes of commercially exploitable wood from scattered trees and rubberwood for each year were finally added to make the total wood increment. The unexploited fraction of the total increment was calculated by subtracting the legal and illegal harvests of roundwood for commercial and small-holder uses from the total increment.

For each parameter, we used the most reliable value found in the literature. The uncertainties on most of these values were not described by a confidence interval because only a small number of estimates were available. Using the available sources, we estimated low and high values for all possible parameters (*SI Text*). In addition to the most reliable estimate, we calculated low and high estimates of displacement and of annual increment of wood volume in forests.

ACKNOWLEDGMENTS. We thank J.-L. Blanchez (FAO/Université Catholique de Louvain) and F. E. Putz (University of Florida, Gainesville) for their comments on a previous version of this manuscript. Errors and omissions remain ours.

- Kauppi PE, et al. (2006) Returning forests analyzed with the forest identity. *Proc Natl Acad Sci USA* 103:17574–17579.
- Chazdon RL (2008) Tropical forest recovery: Legacies of human impact and natural disturbances. *Science* 320:1458–1460.
- Grau HR, Aide M (2008) Globalization and land-use transitions in Latin America. *Ecol Soc* 13:16.
- Kindermann G, et al. (2008) Global cost estimates of reducing carbon emissions through avoided deforestation. *Proc Natl Acad Sci USA* 105:10302–10307.
- Strassburg B, Turner RK, Fisher B, Schaeffer R, Lovett A (2009) Reducing emissions from deforestation—The “combined incentives” mechanism and empirical simulations. *Global Environ Change* 19:265–278.
- Meyfroidt P, Lambin EF (2008) Forest transition in Vietnam and its environmental impacts. *Global Change Biol* 14:1319–1336.
- Meyfroidt P, Lambin EF (2008) The causes of the reforestation in Vietnam. *Land Use Policy* 25:182–197.
- Global Witness (1999) *Made in Vietnam—Cut in Cambodia: How the Garden Furniture Trade Is Destroying Rainforests*. (Global Witness, Washington, DC).
- Barney K (2005) *Central Plans and Global Exports: Tracking Vietnam's Forestry Commodity Chains and Export Links to China*. (Forest Trends, Washington, DC).
- EIA-Telapak (2008) *Borderlines: Vietnam's Booming Furniture Industry and Timber Smuggling in the Mekong Region* (Environmental Investigation Agency—Telapak, London).
- Oliveira PJ, et al. (2007) Land-use allocation protects the Peruvian Amazon. *Science* 317:1233–1236.
- Andam KS, Ferraro PJ, Pfaff A, Sanchez-Azofeifa GA, Robalino JA (2008) Measuring the effectiveness of protected area networks in reducing deforestation. *Proc Natl Acad Sci USA* 105:16089–16094.
- Sohngen B, Brown S (2004) Measuring leakage from carbon projects in open economies: A stop timber harvesting project in Bolivia as a case study. *Can J Forest Res* 34:829–839.
- Gan J, McCarl BA (2007) Measuring transnational leakage of forest conservation. *Ecol Econ* 64:423–432.
- Aukland L, Costa P, Brown S (2003) A conceptual framework and its application for addressing leakage: The case of avoided deforestation. *Clim Policy* 3:123–136.
- Roca J (2003) Do individual preferences explain the Environmental Kuznets curve? *Ecol Econ* 45:3–10.
- Murray B, McCarl B, Lee H (2004) Estimating leakage from forest carbon sequestration programs. *Land Econ* 80:109–124.
- Shryock HS, Siegel JS (1971) *The Methods and Materials of Demography*. (US Government Printing Office, Washington, DC).
- England SB, Kammen DM (1993) Energy resources and development in Vietnam. *Annu Rev Energy Environ* 18:137–167.
- McElwee P (2004) You say illegal, I say legal: The relationship between ‘illegal’ logging and land tenure, poverty, and forest use rights in Vietnam. *J Sustainable Forest* 19:97–135.
- Tuynh VH and Phuong PX (2001) in *Forests Out of Bounds: Impacts and Effectiveness of Logging Bans in Natural Forests in Asia-Pacific*, eds Durst PB, Waggener TR, Enters T, Tan LC (FAO Regional Office for Asia and the Pacific, Bangkok, Thailand).
- Ministry of Agriculture and Rural Development. (2003) *Forest Sector Manual—Chapter 3: Forestry Development Orientation* (Ministry of Agriculture and Rural Development—Forest Sector Support Partnership, Ha Noi).
- Forde A, De Vylder S (1996) *From Plan to Market: The Economic Transition in Vietnam* (Westview, Boulder, CO).
- Glewwe P, Agrawal N, Dollar D, eds (2004) *Economic Growth, Poverty, and Household Welfare in Vietnam* (World Bank, Washington, DC).
- Castren T (1999) *Timber Trade and Wood Flow Study - Country Report Vietnam* [Regional Environmental Technical Assistance 5771 Poverty Reduction and Environmental Management in Remote Greater Mekong Subregion (GMS) Watersheds Project (Phase II)].
- Ministry of Agriculture and Rural Development (2001) *Five Million Hectare Reforestation Program Partnership. Synthesis Report* (Ministry of Agriculture and Rural Development, Ha Noi).
- Phan SH (2004) The changing administration and role of forestry in the economy of Vietnam. *Small-Scale Forest Econ Manage Policy* 3:85–98.
- Mather AS, Needle CL (1998) The forest transition: A theoretical basis. *Area* 30:117–124.
- Green RE, Cornell SJ, Scharlemann JPW, Balmford A (2005) Farming and the fate of wild nature. *Science* 307:550–555.
- Hecht SB, Kandel S, Gomes I, Cuellar N, Rosa H (2006) Globalization, forest resurgence, and environmental politics in El Salvador. *World Dev* 34:308–323.
- Izquierdo AE, Grau RH (2009) Agriculture adjustment, land-use transition and protected areas in northwestern Argentina. *J Environ Manage* 90:858–865.
- Matson PA, Vitousek PM (2006) Agricultural intensification: Will land spared from farming be land spared for nature? *Conserv Biol* 20:709–710.
- Walker R (2008) Forest transition: Without complexity, without scale. *Prof Geogr* 60:136–140.
- Rudel TK, et al. (2005) Forest transitions: Towards a global understanding of land use change. *Glob Environ Change* 15:23–31.
- Perz SG (2007) Grand theory and context-specificity in the study of forest dynamics: forest transition theory and other directions. *Prof Geogr* 59:105–114.
- Laurance WF (2008) The need to cut China's illegal timber imports. *Science* 319:1184–1185.
- Kull CA, Ibrahim CK, Meredith TC (2007) Tropical forest transitions and globalization: neo-liberalism, migration, tourism, and international conservation agendas. *Soc Nat Resour* 20:723–737.
- Aide TM, Grau HR (2004) Globalization, migration, and Latin American ecosystems. *Science* 305:1915–1916.
- Eliasch J (2008) *Eliasch Review—Climate Change: Financing Global Forests*. (UK Office of Climate Change).
- Putz FE, et al. (2008) Improved tropical forest management for carbon retention. *PLoS Biol* 6:e166.
- Johnson S (2003) Estimating the extent of illegal trade of tropical forest products. *Int Forest Rev* 5:247–252.
- Enters T (2001) *Trash or Treasure? Logging and Mill Residues in Asia and the Pacific* (FAO, Bangkok, Thailand).
- Schloenhardt A (2008) *The Illegal Trade in Timber and Timber Products in the Asia-Pacific Region*, Research and Public Policy Series No. 89 (Australian Institute of Criminology, Canberra).
- Blanchez JL (1997) *Forest Resources and Roundwood Supply in the Asia Pacific Countries: Situation and Outlook to the Year 2010* (FAO, Rome).
- Dudley RG (2004) Modeling the effects of a log export ban in Indonesia. *Syst Dyn Rev* 20:99–116.