Supporting Information

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SI Materials and Methods

Sources of Land Cover Data. Data on agricultural areas were obtained from FAOSTAT (http://faostat.fao.org/), combining the categories of "Arable land and permanent crops" and "Permanent meadows and pastures." Forest cover data were reconstructed based on different data sources for each country, with spline interpolation between the data points. For Bhutan, the Food and Agriculture Organization of the United Nations (FAO) *Global Forest Resources Assessment* (FRA) of 2005 (1) was used for data for 1990, 2000, and 2005. For Brazil, FAO FRA 1958 data (2) were used for 1961; FAO FRA 2005 (1) supplied data for 1990, 2000, and 2005; and annual deforestation rates from FAO FRA 1980 (3) were used for the period 1975–1990. For Cameroon, FAO FRA 2005 (1) was used for data for 1990, 2000, and 2005, and annual deforestation rates from FAO FRA 1980 (4) were used for the period 1980–1990. For Chile, FAO FRA 1958 (2) was used for data for 1958, FAO FRA 1963 (5) was used for data for 1963, FAO FRA 2005 (1) was used for data for 1990, 2000, and 2005, and annual deforestation rates from FAO FRA 1980 (3) were used for the period 1980–1990. For China, data were from ref. 6. For Costa Rica, data from ref. 7 were used for 1961, 1980, and 2000. For El Salvador, data from ref. 8 were used for forest-area change from 1992 to 2001. For France, data from ref. 9 were used for 1960, 1970, and 1985, and statistics from Inventaire National Forestier (http://www.inf.fr) were used for 1990–2005. For India, data from the Forest Survey of India (ref. 10 and http://www.fsi.nic.in/) were used for 1973, 1980, 1982, 1986, and 1988; FAO FRA 2005 (1) was used for data for 1990, 200, and 2005. For Indonesia, data for 1950 and 1985 were from ref. 11, and FAO FRA 2005 (1) was used for data for 1990, 2000, and 2005. For Peru, FAO FRA 2005 (1) was used for data for 1990, 2000, and 2005, and annual deforestation rates from FAO FRA 1980 (3) were used for the period 1975–1990. For Vietnam, data for 1958, 1975, 1980, 1992, 1995, and 2005 were from ref. 12, and the website of the Forest Protection Department (http://www.kiemlam.org.vn) supplied data for 2007.

Sources of Data and Parameters for the Calculation of Displacement and Absorption. Data and parameter sources were FAOSTAT (http://faostat.fao.org/) for data on production, trade, average yields, estimates of wastes during transport and storage, carcass weight of animals, composition of feed crops, and pasture area by country; the COMTRADE database (http://comtrade.un.org/db/) for sources of imports and for trade in processed wood products not included in FAOSTAT; refs. 13 and 14 for parameters of animal production systems for different regions of the world; ref. 15 for global pasture area in 2000 at 5′ resolution (http://www.geog.mcgill.ca/~nramankutty/Datasets/Datasets.html for global pasture area in 1961–2007 at 0.5° resolution); and refs. 16 and 17 for parameters of wood production systems globally and by country. Parameters from ref. 13 were available for 1970, 1995, and 2030, were linearly interpolated between these years, and were assumed to remain constant before 1970.

Displacement of Crop Production. In the following discussion, the term "target country" refers to the country for which displacement is calculated. For each country, all imports of agricultural products for 1961–2007 (excluding animal products) were compiled. A subset of products was selected, defined to represent at least 80% (usually >90%) of the total quantity of imports of each year. For each of the main products, the proportion of imports coming from the main source countries (representing at least 85% of the imports of this product) in 1970, 1980, 1995, 2000, and 2005 were identified in the COMTRADE database. These proportions were linearly interpolated for the missing years in the period 1971–2005. For the periods 1961–1969 and 2006–2007, proportions being imported from different countries were assumed to remain constant as in 1970 and 2005, respectively. The annual average waste-adjusted yield for each of the main imported products was calculated based on the proportions of source countries. Waste adjustment accounts for losses during transport and storage. For derived products such as oil, we used the total waste-adjusted yields, because the leftovers often are used as bran, cakes, and other feedstuffs. The land-use demand associated with these leftovers thus was allocated to their consumers. Except for the kernels, which are a small fraction of the fruit, leftovers from pressing oil palm fruits are not used as cake. Therefore, for oil palm and derivates, a specific yield adjustment factor of 0.25 (from FAO Commodity Trees) was applied to account for wastes occurring during the conversion of palm fruit to oil. Waste-adjusted yields for a given year were calculated by dividing base yields in a source country by the ratio of the total domestic supply plus waste to total domestic supply for this country. Based on these yields, the annual area needed to produce the main products imported was calculated and was extrapolated to the annual area required for the total quantity of imported products based on the proportion of imports included in the main products. This value represented the gross displacement for crop products.

Similarly, for each country, all exports of agricultural products for 1961–2007 (excluding animal products) were compiled, the main products were selected, waste-adjusted yields were calculated, and the annual area required to produce the total quantity of exported products (i.e., the gross absorption) was estimated.

The difference between the areas needed to produce imports and exports for each year represents the area associated with displacement of production of crop products consumed in the country. A negative value represents net absorption, and thus an export of embodied land abroad; a positive value represents net displacement, and thus an import of embodied land from abroad.

Displacement of Animal Production. First, for each world region (according to ref. 13), the characteristics of the animal production systems were calculated. The productions of the main categories of animal products for 1961–2007 were compiled: meat of bovines, ovines, pigs, poultry, and dairy products, added to exports of live animals (bovine, ovine, pigs, and poultry) (converted to meat weight using annual carcass-weight data for the region from FAOSTAT). The annual quantity of cattle, dairy cows, sheep, and goats in "pasture" versus "mixed and landless" production systems were calculated using the proportions of animals in each production system (13). The annual total weight of feed needed for the amount of meat and milk produced then was calculated using feed-conversion ratios for different production systems (13). The annual total weight of grass and feed crops needed then was derived using the composition of feed for different production systems (13). Then, based on the total amount of grass needed and the annual area of pasture (from ref. 15), and on the proportion of different crops in the animal feed (from table 3.24 of ref. 14), the annual yields of pasture and of feed crops were calculated for each region. The land-use demand associated with feed obtained from scavenging on roadsides was considered as null.

Second, for each country, imports of the main categories of animal products for 1961–2007 were compiled: meat of bovines,

ovines, pigs, poultry, dairy products, and live animals (bovine, ovine, pigs, and poultry). Eggs and raw material from animal sources, including wool, skins, and hides, were not included. For each product, the proportion of imports coming from the main source regions (representing at least 85% of the imports of this product) were identified for 1970, 1980, 1995, 2000, and 2005 in the COMTRADE database, were linearly interpolated for the period 1971–2005, and were assumed to remain constant before 1970 and after 2005. For each source region, the live animals traded were converted to meat equivalents using carcass-weight figures for the source region, to obtain the total annual quantity of meat exported from this region to the target country. Then, based on the production system of the region, the annual area of pasture and croplands required to produce the exports from this region to the target country, or gross displacement, was calculated.

For exports, the same categories of products were compiled for 1961–2007 for each target country, and the annual area of pasture and croplands required to produce these exports, or gross absorption, was calculated based on the production system of the region of the target country. As for crop products, the balance of area needed for imports and for exports for each year then was calculated to determine the area associated with net displacement of production of animal products consumed in the country.

Displacement of Wood Production. For each country, all imports of wood products for 1961–2007 were compiled from FAOSTAT for raw and primary processed wood products and from COMTRADE for secondary processed wood products (SPWP). For some countries, SPWP data for the earliest years were missing and were estimated by extrapolation of the proportion of SPWP imports compared with raw and primary processed wood imports during the previous years. The traded quantities (in cubic meters, tons, or kilograms) were converted to cubic meters of roundwood equivalent (RWE) by using conversion factors for each product from ref. 16. A subset of products defined to represent at least 80% of the total quantity of RWE imports for each year was selected. For each of these products, the proportions of imports coming from the main source countries (representing at least 85% of the imports of this product) in 1970, 1985, 1995, 2000, and 2005 were identified in the COMTRADE database, were linearly interpolated for the period 1971–2005, and were assumed to remain constant before 1970 and after 2005. Then, using data from ref. 17, the annual area of forest that had to be exploited to produce these quantities in each source country was calculated based on gross annual increment (GAI) of commercial species for exploitable forests for each country. Finally, the annual area required for the total quantity of imported products, or gross displacement, was extrapolated, based on the proportion of imports included in the main products.

Similarly, all exports of wood products for 1961–2007 were compiled from the same sources and converted to RWE, and the annual area required to produce this quantity of exported products, or gross absorption, was calculated based on GAI of the target country from ref. 17. The balance of area needed for imports and for exports for each year then was calculated, representing the area associated with net displacement of production of wood products consumed in the country.

Association of Displacement, Land Use, and Forest-Cover Change. Bivariate regressions were used instead of correlations because of the panel structure of the data and the presence of serial correlation. First, the variables of forest cover and net displacement were standardized and normalized for each country (i.e., subtracting the mean and dividing by the SD for that country's time series), allowing us to compare the association between the evolution of the variables, regardless of country-specific differences in baseline forest cover and displacement (e.g., caused by biophysical conditions and structural trade patterns). Second, linear panel regressions were performed separately on the countries presenting a forest transition and those without a forest transition. The panel regressions were performed using the plm package in R statistical environment (18). The dependent variable was net displacement/absorption, and the explanatory variable was forest cover. Tests of poolability rejected this specification for the three models. General serial correlation tests and Wooldridge's tests for serial correlation in "short" fixed-effects (FE) panels were all highly significant in the three datasets, showing the presence of significant serial correlation in the regressions (18, 19). This temporal autocorrelation was expected because of the nature of the dataset. Wooldridge's first-difference (FD)-based tests were significant for both FE and FD models for the three datasets, showing that neither FE nor FD allowed correcting for the serial correlation. Thus, White–Arellano heteroscedasticity and autocorrelation (HAC)-consistent estimators of covariance were used to estimate the SEs and the significance of the regression parameters (18, 19). Then, gross domestic product and gross domestic product per capita at constant prices (from Heston et al., 2009, Penn World Table version 6.3, Center for International Comparisons of Production, Income and Prices at the University of Pennsylvania, http://pwt.econ.upenn.edu/) and their logs were added separately to the panel regressions. Third, ordinary least squares (OLS) linear regressions with the same dependent and explanatory variables were performed using the lm package in R. In each country, the residuals of the OLS regressions showed significant serial correlation of order 1 (or possibly 2, in a few cases) according to autocorrelograms and Durbin–Watson tests (20). For a consistent correction for all countries, robust HAC estimators of covariance were computed using the sandwich package in R, and Andrew's (1991) method of estimating weights (21). Using the Newey–West method to estimate weights yielded very similar results. No prewhitening was applied.

Uncertainties and Possible Biases. A full quantitative assessment of uncertainties regarding forest cover or displacement/absorption was not feasible because of the lack of quantitative estimates of uncertainties for several of the variables and parameters. For crop and animal products, uncertainties exist in the time-series of FAO data on trade, yields, and wastes and in the data from other sources on livestock production systems and pasture areas. However, there was no reason to believe that there was a systematic bias that would have either under- or overestimated gross or net displacement.

For forestry products, the uncertainties associated with the conversion of traded products into land-use demand were expected to be higher because the effect on forests of producing and harvesting timber depends largely on the forestry-management practices. However, there was no evidence that these uncertainties led to a systematic bias in over- or underestimating the land-use demand associated with trade of wood products. The yields (GAI) were calculated for natural and planted forests and thus incorporated the effects of country-specific biophysical conditions, types and composition of forests, and forestry intensification (level and type of management and relative importance of plantations and managed and natural forests). These GAI were constant for each country throughout the whole period. Using time-varying yields would have given more accurate estimates. However, there were no available values of timber yields that were global in scope and consistent per country or world region over several time periods. The values we used (17) have been used previously in several studies to calculate ecological footprints and embodied land-use demands (e.g., 22, 23, 24) or econometric models of timber markets (e.g., 25). Second, the values we used were representative of the latter part of the study period (the 1990s and 2000s) and therefore might have overestimated yields for the early decades (the 1960s and 1970s) for several countries. However, international trade was comparatively low during these earlier decades, so the potential bias did not greatly affect our estimates of total displacement.

The land-use demand associated with forestry products also depends on whether the land is converted afterward for agriculture. In that case, the actual land-use demand satisfied by harvesting timber and producing crops abroad could be less than calculated here because the timber and crops could come from the same area. However, in tropical regions, most of the wood cut when clearing agricultural plots is burned or left to decay on site or is used as firewood or other local uses and does not enter international markets (26, 27).

Harvesting wood from plantations does not create deforestation as long as trees are replanted afterward, except when new plantations are created from the conversion of natural forests (a process that, according to the FAO definition, is not deforestation). In 1995, around 80% of the global industrial roundwood production came from natural forests, and this proportion was higher in tropical regions (28). However, intensively managed forest plantations increasingly contribute the world's timber supply (29).

Sylvicultural practices can allow simultaneous increases in harvests and in biomass stock in the forest (30). The land-use demand associated with traded wood products thus could be overestimated, mainly for European countries and, to a lesser extent, for other developed countries. Sustainably managed forests represented only 24% of the global industrial roundwood production in 2007 (31).

For many tropical or developing countries, poor logging and processing practices can lead to high amounts of wastes, increasing the impact on forest per cubic meter of wood product compared with the expected GAI (e.g., 32, 33). The conversion factors of RWE that we used (16) were closer to the performances of industrialized countries and thus could have underestimated the land-use demand associated with displacement.

The timber trade is largely regional. Because the countries in our sample were mainly developing tropical countries, most of the imported wood came from other tropical countries. In tropical regions, the fraction of wood coming from sustainably managed forests is almost null (31), and forestry-management practices are less conservative than in European countries.

In conclusion, for our sample of countries, displacement of land-use demand for forestry products from one country was likely to affect natural forests elsewhere, mainly in the tropics. Uncertainties associated with the effects of sylvicultural management and with the effects of logging practices and wood processing were likely to go in opposite directions. Therefore there was no evidence for systematic biases in the estimates of land use demand associated with wood products.

1. Food and Agriculture Organization of the United Nations (2006) *Global Forest Resources Assessment 2005* (Food and Agriculture Organization, Rome).
2. Food and Agriculture Organization of the United Nations (1960) *World Forest Inventory 1958* (Food and Agriculture Organization, Rome).
3. Food and Agriculture Organization of the United Nations (1981a) *Los Recursos Forestales de la America Tropical* (Food and Agriculture Organization, Rome).
4. Food and Agriculture Organization of the United Nations (1981b) *Forest Resources of Tropical Africa* (Food and Agriculture Organization, Rome).
5. Food and Agriculture Organization of the United Nations (1966) *World Forest Inventory 1963* (Food and Agriculture Organization, Rome).
6. Song C, Zhang Y (2010) Forest cover in China from 1949 to 2006. In *Reforesting Landscapes: Linking Pattern and Process*, eds Nagendra H, Southworth J (Springer, Dordrecht, The Netherlands).
7. Kleinn L, Corrales C, Morales D (2002) Forest area in Costa Rica: A comparative study of tropical forest cover estimates over time. *Environ Monit Assess* 73:17–40.
8. Hecht S, Saatchi SS (2007) Globalization and forest resurgence: Changes in forest cover in El Salvador. *Bioscience* 57:663–672.
9. Cinotti B (1996) Evolution des surfaces boisées en France: proposition de reconstruction depuis le début du XIXe siècle. *Revue Forestière Française* 48:547–562.
10. Forest Survey of India. *The State of Forest Report* (Forest Survey of India, Ministry of Environment and Forest, Dehradun, India).
11. FWI/GFW (2002) *The State of the Forest: Indonesia* (Forest Watch Indonesia, Bogor, and Global Forest Watch, Washington, DC).
12. Meyfroidt P, Lambin EF (2008) Forest transition in Vietnam and its environmental impacts. *Global Change Biology* 14:1319–1336.
13. Bouwman AF, Van der Hoek KW, Eickhout B, Soenario I (2005) Exploring changes in world ruminant production systems. *Agric Syst* 84:121–153.
14. Wirsenius S (2000) *Human Use of Land and Organic Materials: Modeling the Turnover of Biomass in the Global Food System.* PhD dissertation (Chalmers Univ of Technology, Goteborg, Sweden).
15. Ramankutty N, Evan AT, Monfreda C, Foley JA (2008) Farming the planet: 1. Geographic distribution of global agricultural lands in the year 2000. *Global Biogeochem Cy* 22:1003–1021.
16. Ollmann H (2001) *Holzbilanzen für die EU und ihre Mitgliedsländer* (Institut für Ökonomie, Bundesforschungsanstalt für Forst und Holzwirtschaft, Hamburg, Germany).
17. Food and Agriculture Organization of the United Nations (1998) *Global Fibre Supply Model* (Food and Agriculture Organization, Rome).
18. Croissant Y, Millo G (2008) Panel Data Econometrics in R: The plm Package. *J Stat Soft* 27:1–43.
19. Wooldridge JM (2002) *Econometric Analysis of Cross-Section and Panel Data* (MIT Press, Cambridge, MA).
20. Wooldridge JM (2006) *Introductory Econometrics: A Modern Approach* (Thomson South-Western, Mason, OH).
21. Zeileis A (2004) Econometric computing with HC and HAC covariance matrix estimators. *J Stat Softw* 11:1–17.
22. Wackernagel M, Monfreda C, Erb KH, Haberl H, Schulz NB (2004) Ecological footprint time series of Austria, the Philippines, and South Korea for 1961–1999: Comparing the conventional approach to an 'actual land area' approach. *Land Use Policy* 21:261–269.
23. Erb KH (2004) Actual land demand of Austria 1926-2000: a variation on Ecological Footprint assessments. *Land Use Policy* 21:247–259.
24. Moran DD, et al. (2009) Trading spaces: Calculating embodied Ecological Footprints in international trade using a Product Land Use Matrix (PLUM). *Ecol Econ* 68:1938–1951.
25. Zhu S, Buongiorno J, Brooks DJ (2001) Effects of accelerated tariff liberalization on the forest products sector: A global modelling approach. *Forest Policy and Economics* 2:57–78.
26. Houghton RA, Hackler JL (2001) *Carbon Flux to the Atmosphere from Land-Use Changes: 1850 to 1990* (Carbon Dioxide Information Analysis Center, US Department of Energy, Oak Ridge National Laboratory, Oak Ridge, TN).
27. Fearnside PM (2000) Global warming and tropical land-use change: Greenhouse gas emissions from biomass burning, decomposition and soils in forest conversion, shifting cultivation and secondary vegetation. *Clim Change* 46:115–158.
28. Food and Agriculture Organization of the United Nations (2000) *The Global Outlook for Future Wood Supply from Forest Plantations* (Food and Agriculture Organization, Rome).
29. Sedjo RA (2001) The role of forest plantations in the world's future timber supply. *Forestry Chronicle* 77:221–225.
30. Kauppi PE, et al. (2010) Changing stock of biomass carbon in a boreal forest over 93 years. *For Ecol Manage* 259:1239–1244.
31. Auld G, Guldbransen LH, McDermott CL (2008) Certification schemes and the impacts on forests and forestry. *Annu Rev Environ Resour* 33:187–211.
32. Enters T (2001) *Trash or Treasure? Logging and Mill Residues in Asia and the Pacific* (FAO, Bangkok, Thailand).
33. Asner GP, et al. (2006) Condition and fate of logged forests in the Brazilian Amazon. *Proc Natl Acad Sci USA* 103:12947–12950.

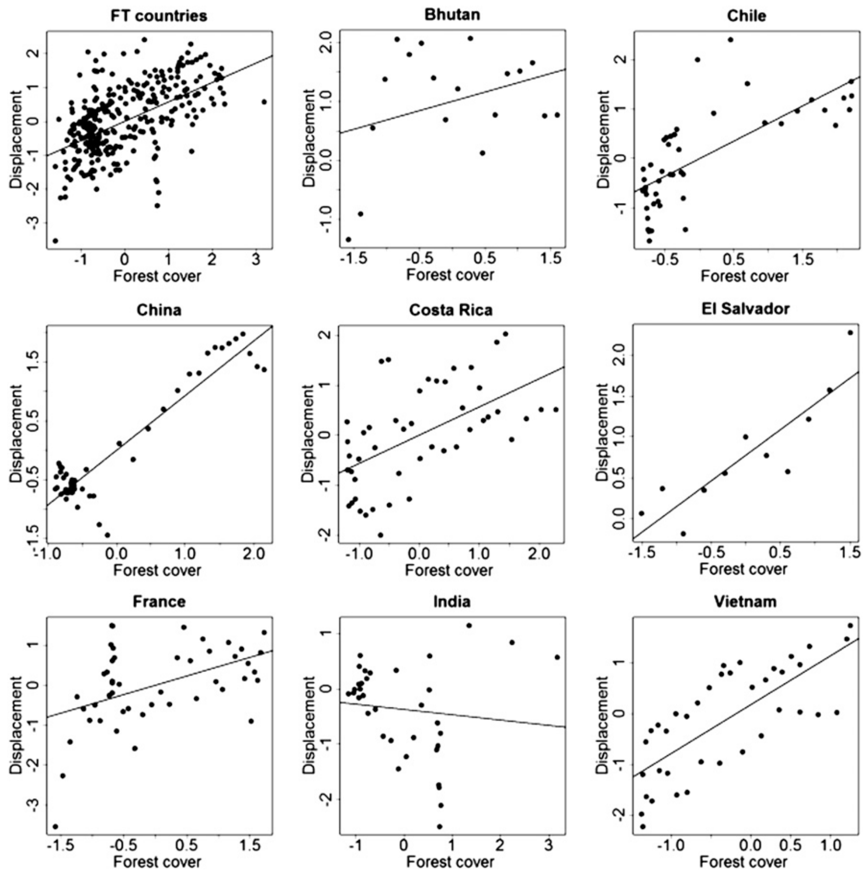

Fig. S1. Plots of the regressions of net displacement/absorption on forest cover for forest-transition (FT) countries, with standardized and normalized variables.

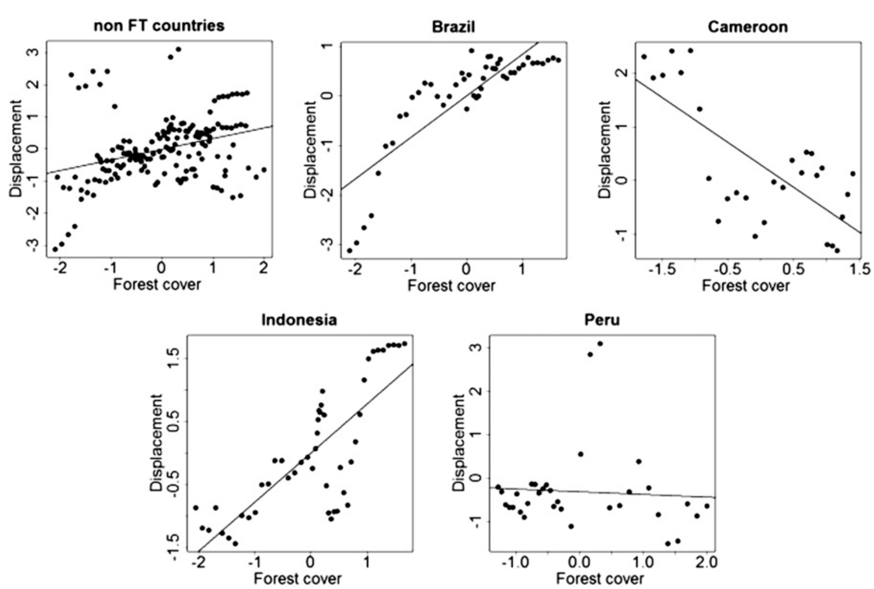

Fig. S2. Plots of the regressions of net displacement/absorption on forest cover for non-FT countries, with standardized and normalized variables.

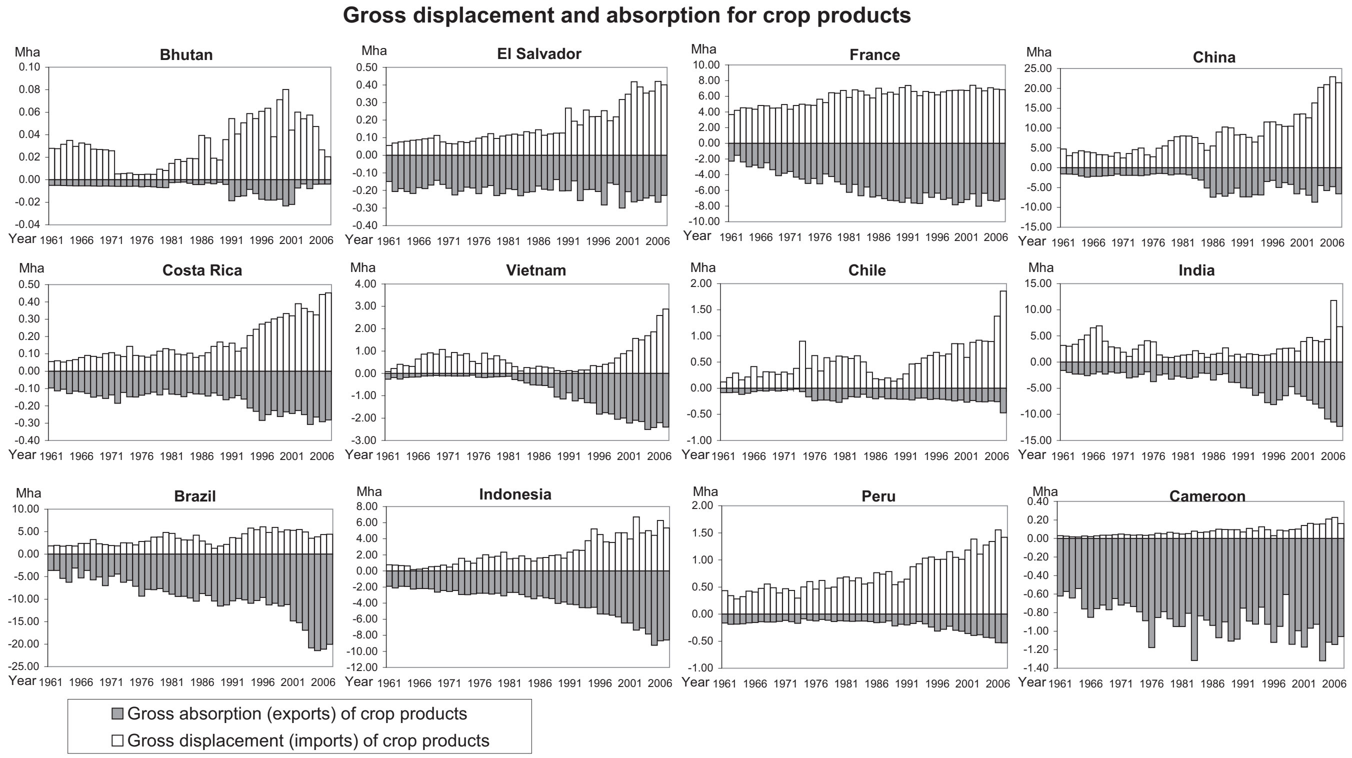

Fig. S3. Graphs of gross displacement and absorption for the crop production sector.

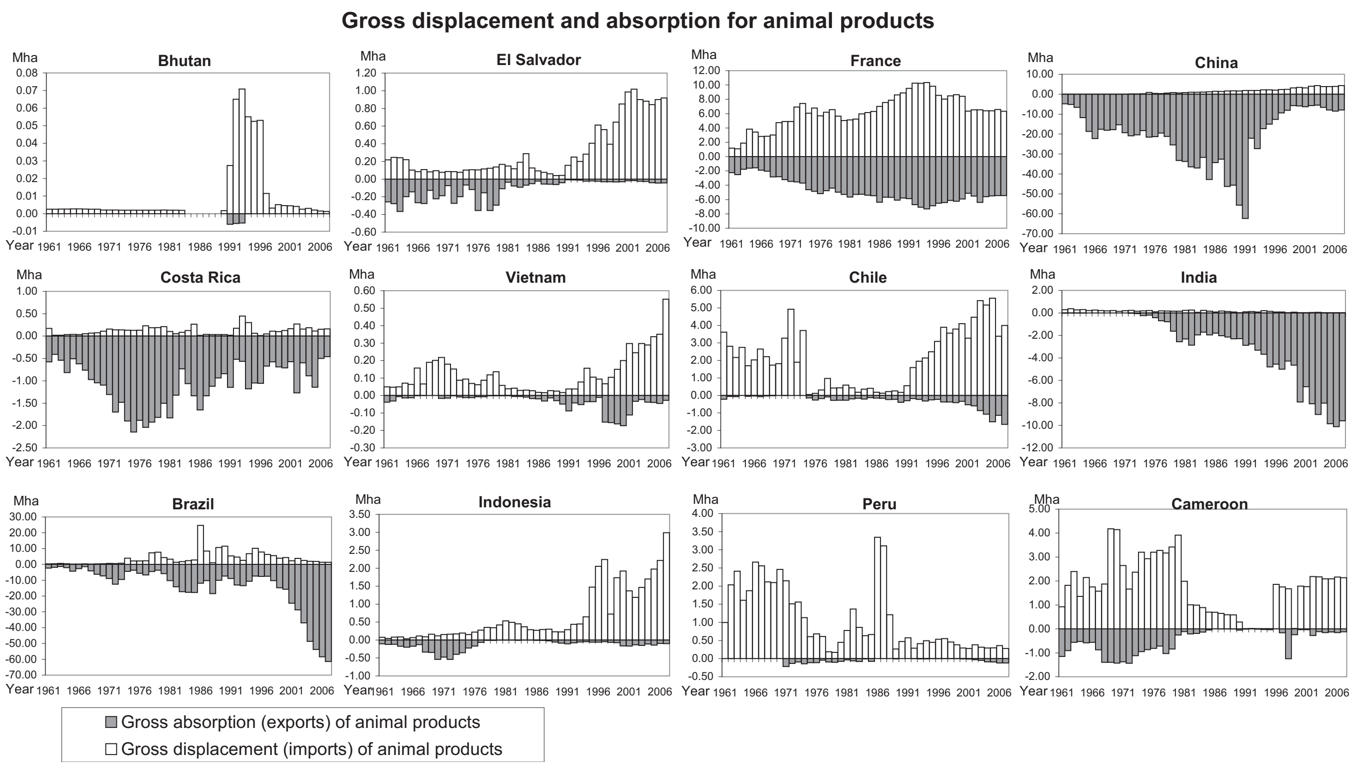

Fig. S4. Graphs of gross displacement and absorption for the animal production sector.

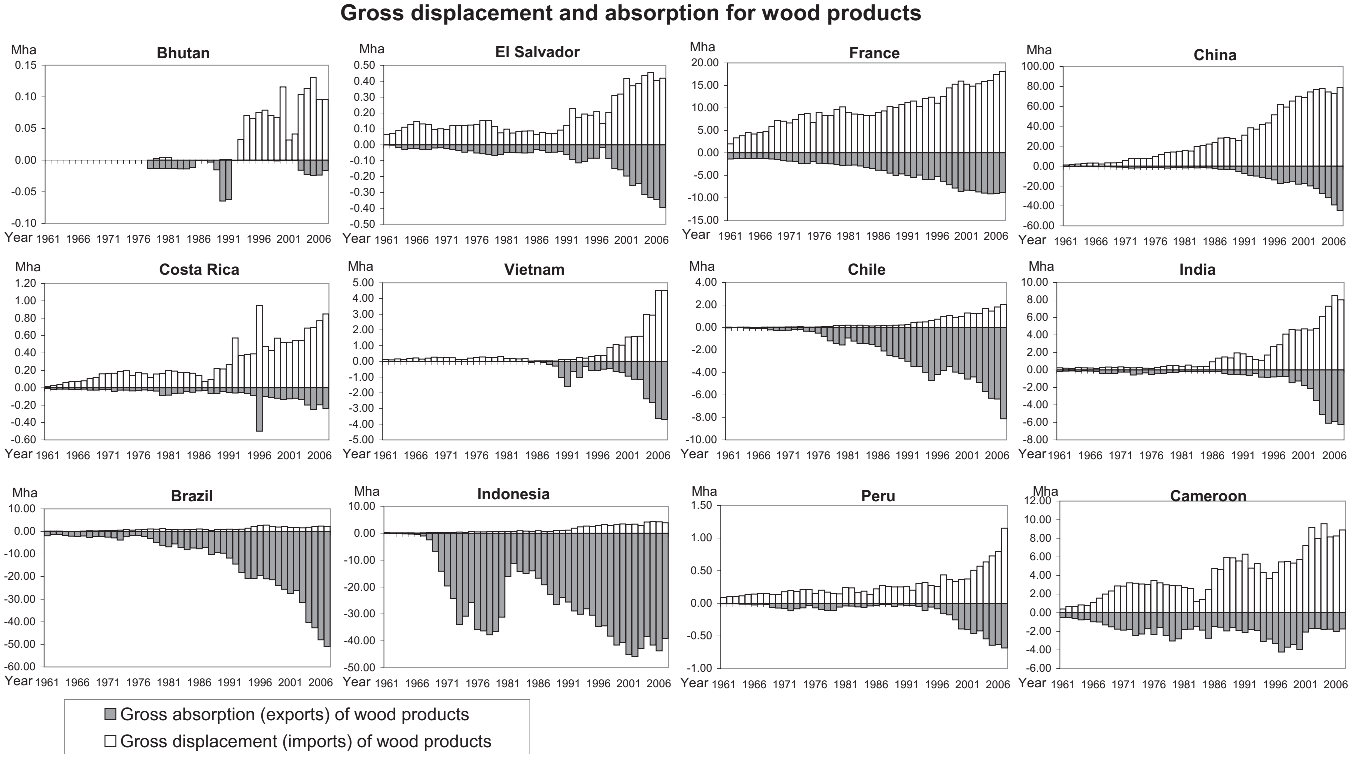

Fig. S5. Graphs of gross displacement and absorption for the wood production sector.

Table S1. Accumulated reforestation and net land sparing for the seven recent FT countries

Country	Total accumulated reforestation (ha/y)	Net accumulated land sparing (total accumulated reforestation − total net displacement) (ha/y)	Gross displacement for forestry products only/total accumulated reforestation (%)	Net displacement for forestry products only/total accumulated reforestation (%)	Net displacement for agricultural (crop + animal) products/total accumulated reforestation (%)	Total net displacement/ total accumulated reforestation (%)
			Since the onset of the forest transition			
Bhutan	1,818,134	−182,012	65	52	58	110
El Salvador	3,080,000	−3,404,834	77	41	169	211
China	1,032,954,548	571,772,373	123	87	−42	45
Chile	14,004,900	32,984,017	140	−564	429	−136
Costa Rica	14,471,175	25,364,335	75	54	−129	−75
Vietnam	35,751,843	48,717,026	69	2	−38	−36
India	65,823,571	241,001,388	121	57	−323	−266
Total	**1,167,904,172**	**916,252,292**	**120**	**74**	**-52**	**22**
Total without India	**1,102,080,601**	**675,250,904**	**120**	**75**	**-36**	**39**
			During the last 5 y			
Bhutan	854,152	226,554	63	51	23	73
El Salvador	2,590,000	−1,683,946	53	18	147	165
China	363,365,434	94,530,464	105	59	15	74
Chile	5,477,000	6,997,359	150	−423	396	−28
Costa Rica	6,101,811	5,896,986	58	41	−38	3
Vietnam	19,893,591	16,420,751	83	15	2	17
India	21,757,000	81,179,219	160	36	−309	−273
Total	**420,038,988**	**203,567,388**	**106**	**49**	**3**	**52**
Total without India	**398,281,988**	**122,388,169**	**103**	**50**	**19**	**69**

Year of the onset of the forest transition (or start of the reforestation period covered by the data): Bhutan, 1990; El Salvador, 1990; China, 1980; Chile, 1980; Costa Rica, 1983; Vietnam, 1991; India, 1980. For the last four columns: a negative number indicates absorption, a positive number <100% indicates a displacement smaller than the accumulated reforestation, and a positive number >100% indicates a displacement larger than the accumulated reforestation.