Forest Product Trade Impacts of an Invasive Species: Modeling Structure and Intervention Trade-Offs

Jeffrey P. Prestemon, Shushuai Zhu, James A. Turner, Joseph Buongiorno, and Ruhong Li

Asian gypsy and nun moth introductions into the United States, possibly arriving on imported Siberian coniferous logs, threaten domestic forests and product markets and could have global market consequences. We simulate, using the Global Forest Products Model (a spatial equilibrium model of the world forest sector), the consequences under current policies of a widespread, successful pest invasion, and of plausible trading partner responses to the successful invasion. We find that trade liberalization would have a negligible effect on U.S. imports of Siberian logs and, consequently, on the risk of a pest invasion. But, if it happened, possibly through trade in other commodities, a successful and widespread pest invasion would have large effects on producers and consumers over the period 2002 to 2030.

Key Words: Asian gypsy moth, trade, invasive species, welfare, spatial equilibrium model

Because exotic pest invasions can have large negative effects on forests, governments have taken steps to limit the risks of introduction. Losses of important timber species to exotic pests have justified phytosanitary policies whose effects on invasion risks may be clear but whose impacts on global markets are not well understood. The risk of exotic pest introductions is typically described as a positive function of trade flows (e.g., Margolis, Shogren, and Fischer 2005). Hence, trade measures focused on potentially infested shipments are cited as cost-effective interventions that can limit introductions and lower expected pest damages nationally (Costello and McAusland 2003, McAusland and Costello 2004, and Margolis, Shogren, and Fischer 2005).

However, trade interventions naturally have consequences for both domestic and international markets. Many studies (e.g., Powell 1997, New Zealand Forest Research Institute 1999, Roberts 1999, and Roberts, Josling, and Orden 1999) have described how phytosanitary requirements such as fumigation, inspection, prohibition of certain packaging materials, tariffs, quotas, and outright trade bans, each offered and applied as effective control and risk mitigation measures, can affect the structure of international production and consumption. Effects include trade shifts due to intervention costs and due to trade policy responses, leading to alterations in prices, product output mixes, and quantities produced and consumed. Research that can quantify the market effects of both a successful invasion and of policies designed to limit its probability of introduction and further spread can lead to better decisions on how to allocate scarce resources and mitigate negative impacts.

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The objective of this analysis is to predict some of the economic consequences of forest-based exotic pest invasions and of specific policies designed to limit their probability and scope. To do this, we describe and apply an empirical model of international trade that incorporates risks of pest invasion and related interventions.[1] The model extends previous work (Costello and McAusland 2003, Barbier and Shogren 2004, and McAusland and Costello 2004) by first describing a theoretical risk-endogenous welfare model, written as a function of all interventions and non-purchased inputs. The objective function of this model is to maximize market welfare (Samuelson 1952), subject to a set of policies and pest-related inventory loss rates. The global trade model employed therefore accounts for the costs of a set of phytosanitary measures, responses of trading partners to these measures and to a successful invasion of an exotic pest in U.S. forests, and the resulting domestic and international product market shifts.

A study that captures both the domestic and the international timber market implications of a potential exotic pest invasion and associated policies would expand the scope of existing research. Published assessments of the consequences of a forest-based exotic pest have usually modeled economic impacts at fine spatial and temporal scales and have typically ignored timber products (e.g., Jakus and Smith 1991, Miller and Lindsey 1993, and Sharov and Liebhold 1998). Only Tkacz et al. (1991) have assessed the market-level impacts of an invasive forest pest, yet that research did not account for the global market interactions between the United States and its trading partners in response to a successful and damaging invasion of U.S. forests. This is unfortunate, because the U.S. forest sector is the dominant player in global markets; catastrophic timber losses would affect, and be affected by, international product markets, redistributing impacts globally. Likewise, domestic and international phytosanitary policies in response to such timber losses would have impacts that transcend U.S. borders.

[1] Examples of interventions include constructing and maintaining detection devices (e.g., traps), conducting periodic aerial surveys, spraying, sanitation cutting in areas of active infestation, altering forest management activities to reduce risks, and funding research to find better ways to limit introductions, spread, establishment, and the ecological and economic damages that such invasive species cause.

A brief review of the importance of the U.S. forest sector can illustrate how failure to prevent introduction or to eradicate an introduced pest could have major consequences for the United States and its trading partners. In 2002, the U.S. forest sector—forestry and logging, and wood and paper manufacturing—added US$148 billion to gross domestic product (1.6 percent of gross domestic product), and had exports worth $18.7 billion, amounting to 2.7 percent of all commodity exports, the second highest in the world, after Canada (Howard 2003). To accomplish this, the sector—excluding furniture—employs over 0.8 percent of the non-farm workforce, or 1.1 million people in 2005 (U.S. Department of Labor 2006). The great extent of the domestic forest resource [226.8 million ha or 5.9 percent of global forest area and 32.2 billion m^3 or 8.2 percent of global forest stock (Food and Agriculture Organization 2001)] and the consequently high rate of industrial roundwood production [405 million m^3 or 25 percent of world production (Food and Agriculture Organization 2005)] explains why the United States is the world's largest producer of wood products (Table 1). The size of the U.S. economy also accounts for the country's status as the world's largest consumer of forest products. In fact, consumption of finished wood products outstrips production (Table 1), making the United States the world's largest importer of wood products—US$32.3 billion in 2002 (Howard 2003)—particularly sawnwood and wood-based panels (Table 1).

The specific application of our model is to the potential introduction of two tree-defoliating Asian insects, the Asian gypsy moth (*Lymantria dispar*) and the nun moth (*Lymantria monacha*). The timber market impacts of a successful invasion by such defoliators were simulated as part of an assessment conducted by Tkacz et al. (1991). The risk assessment was inspired by interest among wood product companies in the late 1980s and early 1990s in importing unprocessed larch (*Larix* spp.) logs from Siberia and the Soviet Far East. The study evaluated the potential consequences of several Asian pests that could enter the United States attached to these softwood logs and ship hulls arriving at American ports. The result of the assessment was a policy effectively banning the import of those logs into the United States,

Table 1. U.S. Production and Consumption of Wood Products, 2002

	Consumption		Production	
Product	1000 m^3 or metric tons	Percent of World	1000 m^3 or metric tons	Percent of World
Industrial roundwood (m^3)	396,153	24.8	404,735	25.4
Sawnwood (m^3)	122,047	31.5	89,151	22.8
Wood-based panels (m^3)	56,089	28.4	40,517	20.7
Fiber furnish (metric tons)	82,720	25.6	91,588	28.6
Paper and paperboard (metric tons)	89,509	27.6	81,792	25.1

Source: Food and Agriculture Organization (2005).

especially due to the risk of an uncontrolled invasion by one of the pests, the Asian gypsy moth,[2] a known aggressive defoliator of many American tree species, including species important to the U.S. timber industry (Roughgarden 1986).[3]

The modeling is accomplished with a modified version of the Global Forest Products Model (Buongiorno et al. 2003). The model predicts country-by-country production, consumption, and trade effects of direct trade measures. The model is adapted to quantify the market and trade impacts of an invasive species that would reduce forest inventories in the United States. For this research, the effects of the invasion and related intervention and trade policies are measured by the differences in market outcomes under varying scenarios of invasion and types of interventions, compared to a base case of no invasion. Thus, as suggested by Barbier (2001), the economic impact of an invasion or a policy is assessed by comparing ex ante and ex post market equilibria. These impacts can then be compared with the costs of the envisaged policy to help in decision making.

Methods

Theory and Empirical Model

Evaluation of the domestic and international impacts of potential moth introductions via infested shipments of Siberian softwood logs imported into the United States is done with the Global Forest Products Model (GFPM) (Buongiorno et al. 2003). The GFPM is a spatial equilibrium model (Samuelson 1952) of the world forest sector. The model is able to quantify the country-by-country effects of shifts in trade barriers, timber demand, and timber inventories (forest stocks)—including the effects of changes in inventory brought about by a damaging exotic invasive. It provides annual projections of production, consumption, and trade for 180 countries and 14 forest product categories. A mathematical description of the GFPM is in Appendix A.

The principal decision maker in the case of a potential invasion is the government, which can impose trade measures, require pre-import treatments, and devote resources to detection and eradication. An invasive pest affects domestic timberland owners by causing a loss in their timber inventories. The inventory loss can take many years. The government planner's decision is to maximize public welfare,[4] narrowly in the timber mar-

[2] Modeling using the Timber Assessment Market Model (Adams and Haynes 1980) showed catastrophic losses to the sector, totaling (in producer price index inflated dollars to 2004) $45 billion (Tkacz et al. 1991, pp. 5–7) of producer plus consumer surplus.

[3] The spread rates of Asian gypsy moth are rapid—more rapid than the European variety that has been spreading from the northeastern United States since 1869—and the detection is difficult and relatively expensive, according to Tkacz et al. (1991). Keena (2003) also documents research showing that important timber species in the United States would be highly vulnerable to these Asian defoliators.

[4] Maximizing the welfare of the forestry sector alone assumes separability of the sector from the rest of the economy. Another model, perhaps a global computable general equilibrium model, could evaluate the effects of imposing this assumption, capturing the effects of forest sector shifts on economy-wide variables. Yet, we contend that the general equilibrium effects on economy-wide variables such as wages, the cost of capital, and exchange rates for the United States would be relatively small, given the size of the U.S. forestry sector relative to that of the whole economy.

ket, W, subject to alternative intervention means (**a**). The forest sector welfare (sum of producer and consumer surplus) in each period is a function of timber inventories (I) and prices (**p**) and the production and consumption activities consistent with inventories and prices.

Inventories and prices are affected by trade measures that alter the introduction and establishment risks, prices, and product flows across borders. These interventions have dynamic effects, as introductions take years to be manifested in tree mortality and because inventory losses and trade measures affect investments in wood processing. The objective function is

$$(1) \quad \max_{\mathbf{a}} W = \sum_{t=1}^{T} [W_t(I_t(\mathbf{a}, \mathbf{x}_t, \mathbf{p}_t(\mathbf{a})) - \mathbf{r}_t'\mathbf{a}_t)]e^{-it},$$

where $t = 1, \ldots, T$ indexes time (years); i is the discount rate; **a** is an $(nT \times 1)$ vector of T annual sets of n intervention approaches $(\mathrm{a}_{1,1}, \ldots, \mathrm{a}_{n,T})$; $\mathbf{x}_t$ is a vector of non-purchased inputs affecting inventory (including biological processes affecting spread and hence inventory loss rates); $\mathbf{r}_t$ is an $(n \times 1)$ vector of costs of interventions; and $\mathbf{a}_t$ is an $n \times 1$ vector of interventions. While the objective function of GFPM is to maximize welfare in the Samuelson (1952) sense, basic outputs reported here are of prices, production volumes, trade, producer revenues, and consumer expenditures.[5]

Inventory, a function of the interventions as well as biological processes, suffers a gradual loss as an uncontrolled pest spreads across the landscape. To the extent that equation (1) ignores other sectors [for example, effects of a pest on ecological services and impacts on trees growing in residential settings—see, for example, Jakus and Smith (1991)], it does not define a global optimum from a societal perspective, but concentrates instead on the forest sector.

A key factor in calculating the expected benefits is the timber inventory losses deriving from an uncontrolled pest invasion. The GFPM contains a system of equations describing the annual roundwood harvest, the growth of forest stock, the change in forest area (the combination of which defines forest inventories), and the evolution of forest stock and forest area over time (Turner, Buongiorno, and Zhu 2006). In each year, the short-run supply (harvest) of roundwood in a country is the sum of harvests of industrial roundwood, other industrial roundwood (wood used in the round), and fuelwood. The harvest volume of each is a function of its price, forest stock, and gross domestic product per capita, where prices and forest stock are determined endogenously.

Each country's forest stock evolves with a growth-drain equation:

$$(2) \quad I_{i,t+1} = \left(1 + g_{it}^{a} + g_{it}^{u} + g_{it}^{u^*}\right) I_{it} - S_{it},$$

where S_{it} is the total roundwood harvest in country i, in year t, g_{it}^{a} is the annual relative (rate of) change in forest stock due to forest area change (afforestation/deforestation), g_{it}^{u} is the rate of forest growth in a given area, without harvest, and $g_{it}^{u^*}$ is the adjusted rate of forest growth in a given area, without harvest. The last is exogenous, representing, for example, the effect of the Asian gypsy and nun moths. The annual relative change of forest area is a function of income per capita (y'), as in the environmental Kuznets curve for deforestation:

$$(3) \quad g_{it}^{a} = \alpha_0 + \alpha_1 (y') + \alpha_2 (y')^2.$$

The annual relative change of forest stock due to growth is a function of a measure of forest density, stock (I_{it}) per unit area (A_{it}):

$$(4) \quad g_{it}^{u} = \gamma_0 \left(I_{it} / A_{it}\right)^{-\alpha}.$$

The parameters (α's and γ_0) of equations (3) and (4) have been estimated with international panel data (Turner, Buongiorno, and Zhu 2006) (see Appendix B).

In this study, forest stock impacts due to invasive species spread over time are captured in equation (2) as an exogenous reduction in forest stock, $g_{it}^{u^*}$, using stock reduction estimates from Tkacz et al. (1991). Diffusion of the pest is de-

[5] The GFPM calculates market equilibria by maximizing the sum of consumer and producer surplus net of transport costs (Samuelson 1952). However, this is only a computational device, and we cannot interpret the level of the objective function nor its change as a measure of the level of welfare or its change.

terministic and assumed linear over time [i.e., non-native habitat affected increases quadratically, as in Roughgarden (1986)]. The resulting reduction in inventory if an invasion occurs is 0.05 percent per year from 2003 to 2010, 0.09 percent from 2011 to 2020, and 0.12 percent from 2021 to 2030.

Simulation Experiments

The simulations assess how different levels of intervention efforts—from trade bans to no effort—to detect or control the spread of the Asian gypsy or nun moths affect forest product production, consumption and trade, forest resource changes, and U.S. domestic welfare in the forest sector. To this end, we compare GFPM projections under four scenarios:

- Scenario 1: The base case, with no moth invasion, the current ban on imports of Siberian softwood logs implemented, and status quo intervention levels for trade in all forest products (i.e., routine inspections, debarking, and annual expected monitoring and eradication costs borne by the public).
- Scenario 2: A lifting of the ban on imports of Siberian softwood logs, with no invasion, but with more intervention—greater port inspection and related costs than in the status quo.
- Scenario 3: A successful moth invasion, which reduces U.S. inventory and results in the ban on imports of Siberian softwood logs being reinstated.
- Scenario 4: An extension of Scenario 3 by adding a ban by other countries on log imports from the United States.

Following is a more detailed description of each scenario.

Scenario 1. In the base case, we simulate with the GFPM a ban on imports of softwood logs from Siberia, with no invasion occurring and no intervention. We obtain (market) revenue and expenditure figures for the United States and for other countries. There is a cost to maintain a perfectly successful detection and eradication system, estimated at about \$5 million per year in the United States.[6] We discount this cost and deduct it from market economic surplus when solving for market equilibria.

Scenario 2. Free trade in Siberian logs and no pest introduction, but with higher fumigation, detection, and eradication costs. These higher costs (interventions) are imposed to lower the probability that a pest would reside in the logs or on the docking ship at a U.S. port. Each year, the government expends $Z_t = u_t * v * zf_t * u_t + bh_t$, where u_t is the number of shipments per year of Siberian logs to the United States, v is the volume per shipment (a constant), and zf_t is the cost of fumigation per unit volume (obtained from the literature and New Zealand data). This cost is paid by the importer and is simulated in the GFPM as an increase in the transport cost from Russia to the United States. bh_t is the annual cost of maintaining a high-level moth detection and eradication system to successfully halt an introduction. The detection and eradication costs for such a widespread infestation, using *Bacillus thurigiensis* (Bt) as the principal eradication measure, is estimated at \$49 million per year.[7]

Scenario 3. Free trade in Siberian logs but with a pest introduction. This assumes that, despite the measures simulated in Scenario 2, a pest would be introduced into the United States and would be established in year $T_1 < T$. As a result, at T_1 there is a ban on softwood log imports from Siberia to the United States, but not from other countries. Nevertheless, the pest would spread and inventory would be destroyed progressively across the range of susceptible timber species. The costs are the same as in Scenario 2.

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[6] Mastro (2005) reports that there have been three outbreaks in the continental United States since 1991. Jenkins (undated) reports a cost of \$17 million for eradication of one single outbreak (based on the 1991 cost figure for an eradication in Oregon in 1991, applying consumer price inflation of 42 percent and inflating to 2005 dollars). Assuming that there had been three outbreaks, from 1991 to 2004, all of which had been contained, implied an annualized cost of \$17 million/outbreak × 3 outbreaks/13 years = \$3.9 million/year. We raised this cost to \$5 million/year to pay for a detection system.

[7] A total figure of \$821 million over 40 years was estimated by an internal report by the U.S. Department of Agriculture and Oregon and Washington's Cooperative Asian Gypsy Moth Eradication Project, in response to a 1992 USDA Animal and Plant Health Inspection Service report. The annual \$49 million cost is obtained using a 3 percent discount rate and 38 percent consumer price inflation since the 1992 study (\$85 million per year using a government projects 7 percent discount rate).

Scenario 4. Free trade in Siberian logs, with a pest introduction and a ban by all other countries on exports of U.S. logs. This extension of Scenario 3, adding the global ban against U.S. log exports, is a plausible response from U.S. trading partners seeking to prevent further transmission of the pest into their countries.

The consequences of each scenario for the United States and for the rest of the world are measured by forest area and forest stock, production, prices, net trade, and present value of consumer expenditures and producer revenues (at a 3 percent real discount rate) from 2003 to 2030.

Data Sources [8]

Estimates of supply and demand elasticities have already been identified and are available in Buongiorno et al. (2003) (see Appendix B). Estimates of the wood supply model parameters are available in Turner, Buongiorno, and Zhu (2006). Information on functions of the probability of introductions given alternative levels of resources applied to interventions are assembled from published studies and expert opinion (e.g., from government agencies of Oregon and Washington, and from information provided by Forest Health Protection of the USDA Forest Service and the USDA Animal and Plant Health Inspection Service). Intervention cost data are derived from estimates from representative international costs. Specifically, costs of methyl bromide treatment were obtained from New Zealand (Hosking 2005)[9] and are set at the average cost of US$2.66/m^3 (NZ$1=US$0.71). This fumigation cost is added to inspection and debarking costs, which, when combined, amount to the "treatment" cost used in modeling. Inspection costs are estimated to be approximately $0.50/m^3. Debarking costs, which we fold into the fumigation costs and are required for U.S. imports, are set at $2.58/m^3, a 2005 estimate based on Han and Renzie (2005).[10] Combined, these three actions bring the total extra trade cost associated with these log imports to $5.74/m^3.

Tkacz et al. (1991) estimated costs for monitoring and detection at "several million dollars every year" (pp. 4-1, 4-5). Sharov, Liebhold, and Roberts (1998), in their 1998 analysis of barrier zone management, also have a monitoring cost estimate, while Sharov and Liebhold (1998) report a cost of monitoring and eradication. We apply only the monitoring cost from Sharov, Liebhold, and Roberts (1998) in our analysis, given that we are already accounting for the cost per invasion.

Experience reported by Mastro (2005) suggests a spread rate of 20 miles per year for a single establishment. This figure ignores human assistance in spread domestically within the United States, which could greatly increase its rate. We assume that timber inventory mortality is complete for timber species of interest in the area of infestation. We have simulated the infestation given this kind of spread rate and can therefore calculate a proportion of inventory affected over the years of uncontrolled invasion, at varying rates of importation of Siberian logs. To limit the scope of our trade-off analysis, we confine our calculations to trade-offs between heightened levels of trade costs (due to fumigation) and to the costs of detection and eradication.

Results

Tables 2 through 7 compare the impacts of all alternative scenarios on prices, production, net trade, forest stock, consumer expenditures, and producer revenues. Each table shows the base level (Scenario 1) solution and then reports differences in outcomes under scenarios 2, 3, and 4.

The free trade scenario with fumigation and debarking of imported logs, compared with the base scenario that continues to ban logs, reveals that allowing importation of Siberian log imports

[8] Model data are available from the authors upon request.

[9] According to Hosking (2005), the cost of methyl bromide treatment at a rate of 120g/m^3 for New Zealand log exports ranges from NZ$1.82 to $2.99/m^3 f.o.b. This cost range is based on an average shipment volume of 42,740m^3 of logs. An additional cost of NZ$1.35/m^3 for treatment at a U.S. port of entry is also added. In U.S. dollars for a U.S. port, the fumigation cost for this study is therefore set at $2.66/m^3.

[10] Han and Renzie (2005) estimate that the cost for processing before loading in the field (at the harvest site), which is comprised primarily of delimbing and debarking, is CAN$3.55/m^3 in 2001 Canadian dollars. Inflated to 2005 (see http://www40.statcan.ca/l01/cst01/econ46.htm), the cost is CAN$3.87/m^3 in April 2005. Using the May 2005 US$/CAN$ exchange rate of $US0.666/$CAN, this processing cost would be US$2.58/m^3.

Table 2. Projected Changes of U.S. Net Trade, 2002 to 2030[a]

	Base Level		Average Annual Difference from Base		
Product	2002	2030	Free Import with Fumigation Cost	Pest Invasion	Pest Invasion with Export Ban
Fuelwood	66	250	-2	-1	-1
Industrial roundwood	8,582	55,544	-3	-2	-25,097
Sawnwood	-32,896	-48,159	-20	-319	6,254
Veneer and plywood	-3,461	-780	0	0	1
Particleboard	-8,296	-27,753	-1	-169	3,522
Fiberboard	-3,815	-8,380	3	-32	571
Mechanical pulp	-67	-290	2	0	52
Chemical pulp	-1,179	-399	1	-4	128
Other fiber pulp	144	318	0	0	-2
Wastepaper	9,970	29,969	-1	1	-13
Newsprint	-5,601	-2,620	-1	-2	89
Printing paper	-5,259	-2,096	3	-27	460
Other paper	3,143	12,991	0	0	0

[a] The unit of measure is thousand m^3 (fuelwood, industrial roundwood, sawnwood, veneer and plywood, particleboard, fiberboard) or thousand metric tons (all pulp and paper products).

Table 3. Projected Changes of Consumer Expenditures and Producer Revenue, 2002 to 2030[a]

	Base Level		Average Annual Difference from Base		
Category	2002	2030	Free Import with Fumigation Cost	Pest Invasion	Pest Invasion with Export Ban
United States					
Consumer expenditures	106,758	144,439	-1	22	-136
Producer revenue	142,534	213,011	-2	-40	781
Total	249,292	357,450	-3	-18	645
World					
Consumer expenditures	444,149	850,362	2	45	138
Producer revenue	632,605	1,190,582	-3	106	315
Total	1,076,754	2,040,944	-1	151	453

[a] The unit of value is million U.S. dollars.

(Scenario 2) has a negligible impact on trade (Table 2). Russian log exports to the United States were small in 2002, amounting to 0.003 percent of total Russian log exports and about 0.01 percent of total U.S. log imports. The projection with GFPM shows that Russian log exports to the United States are 1,300 m^3 per year higher from 2002 to 2030, a quantity that could be handled by a single, partially loaded ship. Given that many more ships from East Asia (including Siberia) arrive at U.S. ports every year, and given that the moth infestations so far have resulted from sources other than logs, the increase in risk due to liberalized Siberian log imports appears negligible.

Under Scenario 2, the total annual cost of fumigation and debarking requirements amounts to \$5,240 in 2002, rising to only \$6,812 by 2030. The present value of the revenues lost by U.S.

Table 4. Projected Changes of Forest Stock, 2002 to 2030 [a]

	Base Level		Average Annual Difference from Base		
Region	2002	2030	Free Import with Fumigation Cost	Pest Invasion	Pest Invasion with Export Ban
Africa	46028	47,109	0	0	-5
North/Central America	69,009	90,276	0	-264	-193
United States of America	32,214	46,770	0	-264	-187
South America	112,636	126,660	0	-1	-16
Asia	33,280	28,953	0	-1	-15
Oceania	12,151	14,827	0	0	-9
Europe	120,408	149,734	1	-2	-40
EU-25 [b]	20,949	28,220	1	-2	-36
World	393,513	457,557	2	-268	-277

[a] The unit of measure is million m^3.
[b] "EU-25" refers to the 25 countries of the European Union.

Table 5. Projected Changes of U.S. Forest Product Production, 2002 to 2030 [a]

	Base Level		Average Annual Difference from Base		
Product	2002	2030	Free Import with Fumigation Cost	Pest Invasion	Pest Invasion with Export Ban
Fuelwood	73,085	32,935	-2	-91	-66
Industrial roundwood	404,735	653,669	-16	-896	-7,785
Sawnwood	89,151	111,286	-20	-326	6,246
Veneer and plywood	15,594	20,051	0	-2	15
Particleboard	18,948	48,031	-1	-176	3,548
Fiberboard	5,975	10,755	3	-33	561
Mechanical pulp	4,245	7,249	2	-5	136
Chemical pulp	48,424	78,413	2	-25	501
Other fiber pulp	245	498	0	0	0
Wastepaper	38,674	76,605	-1	-4	85
Newsprint	5,248	9,173	-1	-3	91
Printing paper	20,964	37,336	3	-29	474
Other paper	55,580	85,430	0	-1	10

[a] The unit of measure is thousand m^3 (fuelwood, industrial roundwood, sawnwood, veneer and plywood, particleboard, fiberboard) or thousand metric tons (all pulp and paper products).

producers, on the other hand, are much higher: $2 million (Table 3). Consumer expenditures are also slightly lower, due to liberalized U.S.-Russia log trade. Clearly, there seems to be no incentive to increase imports of Russian logs, even when not accounting for the pest risk.

These results are in great contrast to the effects of a successful pest invasion (Scenario 3) on U.S. and world forest product markets. Under Scenario 3, U.S. forest stocks (a subset of North/Central America stocks) are 264 million m^3 lower every year from 2003 to 2030 compared to the base case scenario (Table 4). This reduction in stock, which follows from lower domestic U.S. timber product prices, reduces U.S. industrial roundwood harvests by an average of 896 thousand m^3

Table 6. Projected Changes of World Forest Product Prices[a]

	Base Level		Average Annual Difference from Base		
Product	2002	2030	Free Import with Fumigation Cost	Pest Invasion	Pest Invasion with Export Ban
Fuelwood	30	23	0.0	0.0	0.0
Industrial roundwood	66	59	0.0	0.0	0.9
Sawnwood	192	181	0.0	0.1	0.1
Veneer and plywood	396	378	0.0	0.1	0.9
Particleboard	169	159	0.0	0.1	-0.3
Fiberboard	262	258	0.0	0.0	0.3
Mechanical pulp	280	265	0.0	0.1	0.3
Chemical pulp	395	377	0.0	0.1	0.9
Other fiber pulp	741	656	-0.6	-0.2	0.8
Wastepaper	99	126	0.0	0.0	0.0
Newsprint	472	452	0.0	0.1	0.5
Printing paper	766	756	0.0	0.1	0.2
Other paper	669	673	0.0	0.1	0.6

[a] The unit of value is US$/$m^3$ (fuelwood, industrial roundwood, sawnwood, veneer and plywood, particleboard, fiberboard) or US$/metric tons (all pulp and paper products).

Table 7. Projected Changes of U.S. Forest Product Prices, 2002 to 2030[a]

	Base Level		Average Annual Difference from Base		
Product	2002	2030	Free Import with Fumigation Cost	Pest Invasion	Pest Invasion with Export Ban
Fuelwood	30	15	0.0	0.1	0.0
Industrial roundwood	66	56	0.0	0.1	-0.9
Sawnwood	192	202	0.0	0.1	0.1
Veneer and plywood	396	404	0.0	0.3	-2.3
Particleboard	169	167	0.0	0.1	-0.4
Fiberboard	262	270	0.0	0.0	0.3
Mechanical pulp	280	288	0.0	0.2	-1.4
Chemical pulp	395	402	0.0	0.4	-3.2
Other fiber pulp	741	656	-0.6	-0.2	0.8
Wastepaper	99	126	0.0	0.0	0.4
Newsprint	472	476	0.0	0.2	-1.7
Printing paper	766	796	0.0	0.3	-2.3
Other paper	669	667	0.0	0.2	-1.7

[*] The unit of value is US$/$m^3$ (fuelwood, industrial roundwood, sawnwood, veneer and plywood, particleboard, fiberboard) or US$/metric tons (all pulp and paper products).

over the same period (Table 5). The reduction in harvests has little impact on U.S. net trade of industrial roundwood (Table 2). Rather, the greater impact is on U.S. production and net trade of manufactured products, particularly sawnwood, particleboard, and fiberboard. For example, U.S.

sawnwood net imports are 319 thousand m^3 per year higher. In parallel, Canada, Chile, and Finland increase their sawnwood production by 0.09 percent per year, 0.24 percent per year, and 0.59 percent per year, respectively, and their net exports of sawnwood by 0.14 percent per year, 1.57 percent per year, and 1.23 percent per year, respectively.

With a pest invasion (Scenario 3), world and U.S. forest product prices increase slightly (Tables 6 and 7), reflecting the reduction in U.S. production (Table 5). This, coupled with changes in consumption, induces higher U.S. and world consumer expenditures (Table 3). Meanwhile, U.S. producers' gross revenue is reduced, and producers' gross revenue over the world is increased.

A global ban imposed against U.S. log exports in response to a pest invasion in the United States (Scenario 4) aggravates the effect of the pest invasion on world forest stock, although it mitigates the decrease in U.S. forest stock (Table 4). The softening of stock losses in the United States compared to Scenario 3 is largely attributable to reduced harvest levels—industrial roundwood production is about 7 million m^3 per year lower in the United States, compared to Scenario 3, consistent with lower domestic prices. Outside of the United States, higher prices lead to higher harvest rates and hence lower stocks. Lower U.S. roundwood prices (Table 7) lead to higher production of other products with the export ban, especially for sawnwood and particleboard (Table 5). Sawnwood production and net trade increase by more than 6 million m^3 per year, and particleboard production and net trade increase by 3.5 million m^3 per year. The net trade of most U.S. forest products improves, but it worsens significantly for industrial roundwood (Table 2).

The inability of the United States to export logs in Scenario 4 leads to an increase in the world industrial roundwood price relative to Scenario 3, while the U.S. domestic roundwood price decreases. This causes world prices to increase but U.S. prices to decrease for most forest products (Tables 6 and 7). These price changes induce a U.S. gain in competitive advantage and an improvement in U.S. net trade for processed products. U.S. consumer expenditures decrease by \$136 million annually, due to the domestic price drop, while world consumer expenditures increase by \$138 million. U.S. aggregate producer revenue increases by \$781 million each year (due to processed product revenue gains in excess of industrial roundwood revenue losses), because of the increase in domestic production parallel with improved net trade. Meanwhile, world producer revenues increase only by \$315 million each year (Table 3). Taking out the U.S. producer revenue gain, the producer revenue change in the rest of the world is negative.

To check the robustness of these results, we tested the effects of variations of the trade inertia parameters on projected net trade, production, and prices in Scenario 4, a ban on U.S. log exports (Table 8). The trade inertia parameters are critical because they control the range of possible trade changes in GFPM projections. The trade inertia parameters are based on historical annual changes in trade (see Table B.5). The results in Table 8 show that a 10 percent variation in the trade inertia parameters leads to changes in the net trade impact of a pest and a log ban of up to 8 percent. The effect on production and prices is much smaller, except for the effect on waste paper price, which could reach 7 percent. Thus, the results in Scenario 4 are sufficiently robust to support the conclusions, although the error on a particular prediction could be substantial.

Conclusions

We have outlined an empirical approach to evaluating some of the economic effects of a successful pest infestation in the forest sector of the United States and policies to try to prevent it. With the example of an invasion by Asian gypsy and nun moths, we have shown that banning imports of softwood logs from Siberia would have negligible effects on the economy of the U.S. forest sector. This contrasts with the situation in the late 1980s and early 1990s, when there was pressure to increase those imports (Tkacz et al. 1991). At that time, harvests had been much reduced on federal lands in the western United States (Murray and Wear 1998). Mills on the West Coast may have seen Siberian logs as a way to compensate for the lost federal timber. Our modeling shows that, with current markets, there is little economic reason to import Siberian logs. Consequently, current policies that limit such trade seem redundant.

Given the small imports of Siberian logs even under free trade, there seems to be a greater risk

Table 8. Effects of Variations in Trade Inertia Parameters on U.S. Forest Products Net Trade, Production, and Prices, for Scenario of Pest Invasion with Export Ban, 2002 to 2030[a]

	Pest Invasion with Export Ban Scenario		Average Annual Percentage Change in Export Ban Scenario Due to Setting Trade Inertia Parameters			
Product	2002	2030	10% lower	5% lower	5% higher	10% higher
Net Trade						
Fuelwood	66	248	-8.5	-4.9	3.2	5.6
Industrial roundwood	8,582	0	N/A	N/A	N/A	N/A
Sawnwood	-32,896	-34,833	2.6	1.2	-1.0	-1.8
Veneer and plywood	-3,461	-778	8.1	3.9	-3.7	-7.3
Particleboard	-8,296	-16,960	-0.4	-0.1	-0.1	0.0
Fiberboard	-3,815	-6,814	-1.2	-0.6	0.5	0.8
Mechanical pulp	-67	-110	-1.4	0.3	3.8	2.4
Chemical pulp	-1,179	-328	7.0	3.4	-3.3	-6.2
Other fiber pulp	144	317	-3.2	-1.6	1.1	1.8
Wastepaper	9,970	29,840	-4.6	-2.0	1.7	3.0
Newsprint	-5,601	-2,398	4.4	2.2	-1.7	-3.2
Printing paper	-5,259	-1,807	1.3	0.5	-0.9	-1.8
Other paper	3,143	12,992	-6.6	-3.4	3.5	7.2
Production						
Fuelwood	73,085	32,847	0.0	0.0	0.0	0.0
Industrial roundwood	404,735	638,347	-0.5	-0.2	0.2	0.4
Sawnwood	89,151	124,668	-0.7	-0.3	0.3	0.5
Veneer and plywood	15,594	20,076	-0.6	-0.3	0.3	0.5
Particleboard	18,948	58,881	0.3	0.1	-0.1	-0.1
Fiberboard	5,975	12,300	0.8	0.5	-0.3	-0.6
Mechanical pulp	4,245	7,489	0.0	0.0	0.0	0.1
Chemical pulp	48,424	78,818	-0.6	-0.3	0.3	0.7
Other fiber pulp	245	498	-1.9	-1.0	0.7	1.1
Wastepaper	38,674	76,631	-2.1	-0.9	0.8	1.5
Newsprint	5,248	9,396	-1.7	-0.9	0.7	1.3
Printing paper	20,964	37,648	0.1	0.1	0.0	0.0
Other paper	55,580	85,442	-0.7	-0.4	0.4	0.8
Prices						
Fuelwood	30	15	0.0	0.0	0.0	0.0
Industrial roundwood	66	55	-0.6	-0.3	0.3	0.6
Sawnwood	192	202	-0.3	-0.2	0.2	0.3
Veneer and plywood	396	401	-0.2	-0.1	0.1	0.2
Particleboard	169	167	-0.3	-0.2	0.2	0.3
Fiberboard	262	271	-0.1	0.0	0.0	0.1
Mechanical pulp	280	286	-0.3	-0.1	0.1	0.3
Chemical pulp	395	397	-0.4	-0.2	0.2	0.4
Other fiber pulp	741	656	-2.4	-1.2	0.8	1.4
Wastepaper	99	128	-7.1	-3.1	3.2	5.9
Newsprint	472	476	-1.0	-0.5	0.4	0.8
Printing paper	766	793	-0.3	-0.1	0.1	0.2
Other paper	669	665	-0.7	-0.3	0.3	0.5

[a] The unit of measure of net trade and production is thousand m^3 (fuelwood, industrial roundwood, sawnwood, veneer and plywood, particleboard, fiberboard) or thousand metric tons (all pulp and paper products); the corresponding prices are in US\$/m^3 or US\$/metric tons.

of introduction by other means. Recent history shows that Asian gypsy moths may enter the United States aboard any ship. Those risks are significant today, with three successful introductions (and three successful eradications) documented since 1990, the advent of the log import ban. Obviously, the risk exists even without imports of unprocessed softwood logs from that region.

If an invasion were to occur by whatever means, we have shown that it would cause high losses in the U.S. forest product sector, although those impacts would be dampened by the effects of trade and product substitutions. The effects of losses would be especially large on U.S. net trade in roundwood, sawnwood, and particleboard, but relatively smaller in percentage terms on other measures. We estimate that the lost revenues of producers and additional expenditures of consumers would average about $60 million per year, over the period considered. If this average annual loss were to continue for the full 40 years projected by Tkacz et al. (1991), it would be much smaller than the welfare loss projected by that study but far greater than the estimated current annual expenditures on monitoring and eradication. This difference from Tkacz et al. (1991) can be traced to three central reasons. First, GFPM contains different assumptions about market functions (e.g., elasticity assumptions). Second, revenues and expenditures are not the same as welfare. Producer and consumer surplus changes can be larger than simple expenditure and revenue changes when market supply shifts back. Third, GFPM models the global forest sector, not simply the domestic U.S. sector.[11] Therefore, adjustments in trade flows captured by GFPM serve to dampen the domestic economic losses. Trade effects also lead to the terms of trade improvements for the United States in the export ban scenario, which helps to explain why imposition of a log export ban against the United States results in net benefits for the U.S. forest product sector as a whole.

The expected economic losses in the U.S. forest sector due to inventory destruction alone would be in addition to effects of an infestation on ecological and non-timber values of forests. Payne and Strom (1975), Jakus and Smith (1991), and Miller and Lindsey (1993) have described how some of those other costs are manifested for the European variety of the gypsy moth. A worthy additional step in this line of research would be to determine some of those costs for Asian moth infestations.

Likewise, our analysis has ignored the risk of infestation in Canada. A successful, uncontrolled infestation of U.S. forests would raise the risks of similarly large losses of inventory in Canada, the world's second-largest forest product producer and largest exporter to the United States and the world. An important next step in modeling the full impact of an Asian moth invasion would be to recognize its effects on Canadian timber supply.

The analysis done in this paper was deterministic. For a complete probabilistic analysis, more information is needed on the probability of successful invasion by Asian gypsy and nun moths, and about the likely rate of spread following invasion, with or without a barrier zone management program (Sharov and Liebhold 1998, and Sharov, Liebhold, and Roberts 1998).

Although the empirical probability of an uncontrolled invasion in North America, given current monitoring and control approaches, is zero based on recent experience with incipient establishment of the Asian gypsy moth in some states of the United States and Canada, it seems unlikely that the probability of an uncontrolled invasion is zero under the current regime. Moreover, we are facing increasing trade, international and domestic, and travel between eastern Asia and the United States. Land uses are also changing rapidly. It is therefore prudent to accept that the expected losses in the U.S. forest sector are not zero and instead are large. The reality of our current knowledge is that we do not fully understand how the probability of introduction varies with multisectoral trade levels or how the probability of uncontrolled escape varies with pest monitoring and control efforts. Understanding how each of these forces may affect the risk of pest introduction and spread is an important area of future research, which could well result in different conclusions about the efficacy of interventions and hence the net benefits of continuing commodity shipments and any contemplated freeing of log imports from Russia.

[11] Indeed, Tkacz et al. (1991, p. 5-4) assumed independence of events among U.S. wood supply regions, thereby ignoring shifts in production to unaffected regions due to stumpage price increases arising from forest loss.

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APPENDIX A: GFPM Mathematical Formulation

Spatial Global Equilibrium [12]

Objective Function

The objective function of the Global Forest Products Model follows Samuelson (1952), identifying production, consumption, and trade flows so that producer plus consumer surplus minus transfer costs is a maximum:

(A.1)
$$\max Z = \sum_i \sum_k \int_0^{D_{ik}} P_{ik}(D_{ik})dD_{ik} - \sum_i \sum_k \int_0^{S_{ik}} P_{ik}(S_{ik})dS_{ik} - \sum_i \sum_k Y_{ik} m_{ik}(Y_{ik}) - \sum_i \sum_j \sum_k c_{ijk} T_{ijk},$$

where i,j = country, k = product, P = price in U.S. dollars of constant value, D = final product demand, S = raw material supply, Y = quantity manufactured, m = cost of manufacture, T = quantity transported, and c = cost of transportation.

End Product Demand

(A.2)
$$D_{ik} = D_{ik}^{*}\left(\frac{P_{ik}}{P_{ik,-1}}\right)^{\delta_{ik}},$$

where D^* = current demand at last year's price P_{-1}, and δ = price elasticity of demand (Table B.1). D^* depends on last year's demand, and country GDP growth [equation (A.7)].

Primary Product Supply

(A.3)
$$S_{ik} = S_{ik}^{*}\left(\frac{P_{ik}}{P_{ik,-1}}\right)^{\lambda_{ik}},$$

where S^* = current supply at last year's price, and λ = price elasticity of supply (Table B.2). S^* depends on last year's supply, and on exogenous or endogenous supply shifters [equations (A.8) and (A.9)].

For recycled paper, $S_{ik} \le S_{ik}^{U}$, where S^U = upper bound on supply, which depends on domestic paper consumption in the previous year [equation (A.10)].

Country total wood supply is $S_i = S_{ir} + S_{in} + \theta_i S_{if}$, where r = industrial roundwood, n = other industrial roundwood, f = fuelwood, and θ = fraction of fuelwood that comes from the forest (Table B.3). $S_i \le I_i$, where I_i = forest stock.

Material Balance

(A.4)
$$\sum_j T_{jik} + S_{ik} + Y_{ik} - D_{ik} - \sum_n a_{ikn} Y_{in} - \sum_j T_{ijk} = 0 \quad \forall i,k,$$

where a_{ikn} = input of product k per unit of product n (Table B.4). The shadow prices of the material balance constraints give the market clearing prices, P.

Trade Inertia

(A.5)
$$T_{ijk}^{L} \le T_{ijk} \le T_{ijk}^{U},$$

where the superscripts L and U refer to lower and upper bounds [see equation (A.12)], respectively.

Manufacturing Cost

Manufacturing is represented by input-output coefficients and a manufacturing cost (Table B.4). The latter is the cost of the inputs not recognized explicitly by the model (labor, energy, capital, etc.):

(A.6)
$$m = m_{ik}^{*}\left(\frac{Y_{ik}}{Y_{ik,-1}}\right)^{s_{ik}},$$

where m^* = current manufacturing cost at last year's output, and s = elasticity of manufacturing cost with respect to output (Table B.4). m^* depends on last year's manufacturing cost.

[12] All variables refer to a specific year. The software and documentation for the GFPM can be downloaded from http://www.forest.wisc.edu/facstaff/buongiorno/book/GFPM.htm.

Market Dynamics [13]

Shifts of Demand

(A.7) $$D^* = D_{-1}(1+\alpha_y g_y) \ ,$$

where g_y = GDP annual growth rate, and α = elasticity (Table B.1).

Shifts of Supply

Industrial roundwood and fuelwood:

(A.8) $$S^* = S_{-1}(1+\beta_I g_I + \beta_{y'} g_{y'}) \quad \text{for } k = r, n, f,$$

where g_I = rate of change of forest stock [equation (2)], $g_{y'}$ = GDP per capita annual growth rate, and β = elasticity (Table B.2).

Waste paper and other fiber pulp (Table B.2):

(A.9) $$S^* = S_{-1}(1+\beta_y g_y) \ .$$

The upper bound on waste paper supply shifts according to

(A.10) $$S^U = \sum_k r_k D_{k,-1} \ ,$$

where r_k is the maximum possible recovery rate for paper of grade k, which may change exogenously over time.

Changes in Manufacturing Coefficients

The input-output coefficients, the a_{ikn}'s in equation (A.4), may change exogenously over time, in particular to reflect increasing use of recycled paper in paper manufacturing (Table B.4).

Changes in Freight Cost and Tariff

The transport cost for commodity k from country i to country j in any given year is

(A.11) $$c_{ijk} = f_{ijk} + t_{jk}^I \left(f_{ijk} + P_{ik,-1} \right),$$

where c = transport cost, per unit of volume, f = freight cost, per unit of volume, t^I = import ad-valorem tariff (Table B.5), and P_{-1} = last year's equilibrium export price. The import tariffs may change exogenously over time (Table B.5).

[13] Unless otherwise indicated, variables and parameters refer to one country, one commodity, and one year.

Changes in Trade Inertia Bounds

(A.12) $$T^L = T_{-1}(1-\varepsilon)$$
$$T^U = T_{-1}(1+\varepsilon) \ ,$$

where ε equals the upper or lower bound on relative change in trade flow (Table B.5).

APPENDIX B: GFPM Parameters for the United States

Table B.1. Price and Income Elasticities of Demand

Product	Price	Income
Fuelwood	-0.62	-1.50
Other industrial roundwood	-0.05	-0.58
Sawnwood	-0.16	0.32
Veneer and plywood	-0.13	0.10
Particleboard	-0.24	1.25
Fiberboard	-0.52	0.82
Newsprint	-0.05	0.10
Printing and writing paper	-0.15	0.50
Other paper and paperboard	-0.06	0.40

Table B.2. Price, GDP per Capita, and Forest Stock Elasticities of Supply

Product	Price	GDP per Capita	Forest Stock
Fuelwood	2.00	0.00	1.50
Industrial roundwood	0.80	0.80	0.50
Other industrial roundwood	0.80	0.80	0.50
Other fiber pulp	0.80	1.00	
Waste paper	0.80	1.00	

Table B.3. Forest Resource Parameters

Parameter	Unit	Value
Forest stock	(10^6 ha)	32,214
Forest stock growth rate	(% yr^{-1})	3.20
Forest area	(10^3 ha)	226,776
Rate of forest area change	(% yr^{-1})	0.19
Effect of GDP per capita on forest area growth rate		0.1868
Effect of (GDP per capita)^2 on forest area growth rate		-0.0045
Fraction of fuelwood from forest		1.00

Table B.4. Manufacturing Parameters

Input Product	Manufactured Product	Coefficient (m^3m^{-3}, m^3t^{-1}, or tt^{-1})	Change in Coefficient (tt^{-1})	Manufacturing Cost (US$$m^{-3}$ or US$$t^{-1}$)	Output Elasticity of Manufacture Cost
Industrial roundwood	Sawnwood	1.42		119.5	3.00
Industrial roundwood	Veneer and plywood	2.51		262.8	0.10
Industrial roundwood	Particleboard	1.57		74.1	2.00
Industrial roundwood	Fiberboard	1.45		179.0	2.00
Industrial roundwood	Mechanical pulp	2.15		160.1	3.00
Industrial roundwood	Chemical pulp	3.50		196.0	3.00
Mechanical pulp	Newsprint	0.03	0.000	177.7	0.40
Chemical pulp		0.62	-0.002		
Other fiber pulp		0.00	0.000		
Waste paper		0.45	0.002		
Mechanical pulp	Printing and writing paper	0.17	0.000	468.3	0.10
Chemical pulp		0.67	-0.001		
Other fiber pulp		0.00	0.000		
Waste paper		0.09	0.001		
Mechanical pulp	Other paper and paperboard	0.01	0.000	374.8	0.10
Chemical pulp		0.58	0.000		
Other fiber pulp		0.00	0.000		
Waste paper		0.44	0.000		

Table B.5. Trade Parameters [a]

Product	Ad-valorem Tariff (%)	Tariff Reduction (%yr^{-1})	Freight Cost (US$$m^{-3}$ or US$$t^{-1}$)	Trade Bounds (ε)
Fuelwood	0.0	0.0	6	0.045
Industrial roundwood	0.0	0.0	12	0.051
Sawnwood	0.0	0.0	21	0.050
Veneer and plywood	4.0	0.0	16	0.052
Particleboard	1.0	0.0	7	0.069
Fiberboard	1.0	0.0	10	0.060
Mechanical pulp	0.0	0.0	22	0.063
Chemical pulp	0.0	0.0	32	0.045
Other fiber pulp	0.0	0.0	59	0.100
Waste paper	0.0	0.0	20	0.096
Newsprint	0.0	0.0	24	0.030
Printing and writing paper	1.0	-0.5	46	0.051
Other paper and paperboard	1.0	-0.5	40	0.045

[a] The trade bounds (or trade inertia) parameter, ε in equation (A.12) (Appendix A), is a bound on relative change in trade flow for a particular product, and is set at three times the standard error of the mean percentage change of world imports and exports of that product from 1970 to 1997 (Buongiorno et al. 2003).