Assessment of the Risk of Introduction of *Anoplophora glabripennis* (Coleoptera: Cerambycidae) in Municipal Solid Waste from the Quarantine Area of New York City to Landfills Outside of the Quarantine Area: A Pathway Analysis of the Risk of Spread and Establishment

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ABSTRACT The risk associated with spread of Asian longhorned beetle, *Anoplophora glabripennis* (Motschulsky), from infested areas in New York City to the wide array of landfills across the eastern United States contracted by the city since 1997 was unknown, but of great concern. Landfills, some as far as South Carolina, Virginia, and Ohio, occupied forest types and climates at high risk of Asian longhorned beetle establishment. The city proposed a separate waste wood collection known as the "311 System;" this was estimated to cost federal and state agencies $6.1 to $9.1 million per year, including the cost of processing and disposal of the wood. Pathway analysis was used to quantify the probability that Asian longhorned beetle present in wood waste collected at curbside would survive transport, compaction, and burial to form a mated pair. The study found that in seven alternate management scenarios, risks with most pathways are very low, especially given existing mitigations. Mitigations included chemical control, removal of infested trees, and burial of wood waste in managed landfills that involved multiple-layering, compaction, and capping of dumped waste with a 15-cm soil cover at the end of each day. Although the risk of business-as-usual collection and disposal practices was virtually nil, any changes of policy or practice such as illegal dumping or disposal at a single landfill increased the risk many thousandfold. By rigorously maintaining and monitoring existing mitigations, it was estimated that taxpayers would save $75 to $122 million dollars over the next decade.

KEY WORDS *Anoplophora glabripennis*, eradication, landfills, pathway analysis, wood waste

THE ASIAN LONGHORNED BEETLE, *Anoplophora glabripennis* (Motschulsky), was first detected in New York City in 1996 and is assumed to have originated in wood crating and pallets shipped from China. After its discovery, a rigorous detection and eradication effort was initiated given that Asian longhorned beetle infests tree species predominant in U.S. northern hardwoods, and notably maples (*Acer* spp.).

By spring 2003, >12.9 million tons of municipal solid waste (MSW) (Fig. 1) had been disposed at 56 different landfills located in seven eastern states, some as far as South Carolina, Virginia, and Ohio. Federal and state managers of the Asian longhorned beetle Cooperative Eradication Program (USDA–APHIS 2000) voiced great concern that viable Asian longhorned beetle is at risk of being transported in wood with MSW and of establishing successfully in areas adjacent to the landfills.

Currently, New York (New York City; NYC) does not recycle MSW, and Asian longhorned beetle is almost certainly in woody debris collected at curbside. The actual number is not known but could be in the thousands. A possible solution is to collect, treat, and dispose of wood waste separately within the infested area (Fig. 2). NYC estimated the cost of a separate collection at curbside to be approximately $6.1 to $9.1 million annually, including the cost of processing and disposing of the wood (NYDOS 2003b). Known as the "311 System," it was important to evaluate this option against alternatives in terms of cost, practicality, and effectiveness.

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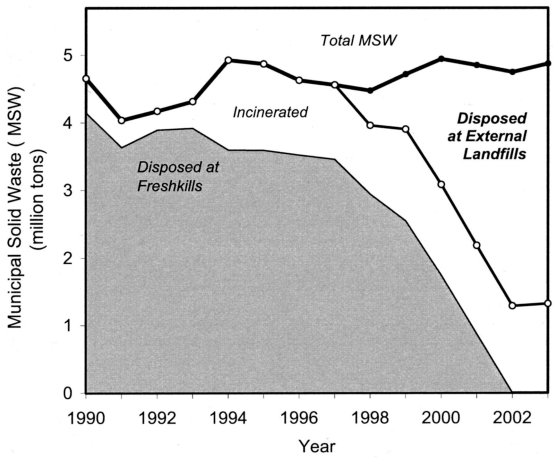

Fig. 1. Annual total tons of municipal solid waste disposed by New York City, 1990–2003. Levels disposed at Fresh Kills Landfill on Staten Island (shaded) shows phase-down of the landfill from 1997 to its closure in 2001. Since 1997, 12.9 million tons of MSW has been disposed at external landfills.

The objective of this study was to quantify the risk of NYC's current practices of inadvertently spreading Asian longhorned beetle in wood waste to landfill sites beyond the boundaries of the city's Asian longhorned beetle quarantine zone (Fig. 2). The pathway of concern was that associated with the routine pickup and disposal of wood debris (e.g., fallen branches and prunings) from quarantined areas. This is mainly the responsibility of New York City's Sanitation Department. A related goal was to evaluate the effectiveness of the department's proposed 311 System, and if justified, recommend other corrective measures.

Materials and Methods

Pathway analysis was used to quantify the probability the beetle was present in MSW collected at curbside and survived yarding, compaction, transport, and burial at a landfill. The end-point was an estimate of the probability that a mated pair of Asian longhorned beetle would escape burial.

Data Sources

Our data included an estimate of the amount of wood waste, and the number, probability, or change in the condition affecting survival and reproduction of Asian longhorned beetle at each point along the wastestream.

Quantity of MSW. Historical data on the annual total tons of residential + institutional MSW (NYDOS 1998, 2001, 2003a, c) was plotted 1990–2003 to determine the total amount sent to landfills over the recent period.

Wood Component of MSW. Details on the amount of wood present in MSW were obtained from SCS Engineers (1992). The data were for "yard wastes" from residential and institutional sources by season, in both general and in periodic bulk waste pickups, 1989–1990.

To obtain a better description of waste wood in MSW, a pass-through survey of waste wood was made at 23 curbside locations in Queens and Bronx boroughs between 9 June and 24 June 2003. The survey counted the pieces of wood in preferred host versus nonhost species, in fresh versus aged/dead condition, and in six diameter classes (<2.5 cm, 2.5–5.1 cm, 5.1–7.6 cm, >7.6 cm, bundles of <91 by 91 cm, and bundles >91 by 91 cm) (R.J.M., unpublished data).

Landfill Operations. A set of ten questions was addressed to the operations manager at 11 of the 56 landfill facilities. Replies were evaluated in terms of how secure the landfill was as a burial site of Asian longhorned beetle.

Asian Longhorned beetle Biology and Behavior

Host Preference. Field and laboratory studies of tree host preference ratings ranging from "nonhost" to "very good host" were transformed to a numeric scale of 0–10. A weighted mean host rating was calculated for trees in each NYC borough; this was the product of number of trees (by species) in each of the street (NYDOS 1996) and nonstreet (D.J.N., unpublished data) surveys, multiplied by species host preference ratings mentioned above.

Potential Asian Longhorned Beetle Distribution. We generated an Ecoclimatic Index for Asian longhorned beetle in the United States similar to that developed by MacLeod et al. (2002) for Europe. The ecoclimatic index (EI) estimates suitability for establishment and growth of a pest based on host and climate distribution (Sutherst et al. 1999). The EI parameters were taken from the MacLeod et al. (2002) model for Asian longhorned beetle in China. It was assumed that the same climatological parameters found in China also would dictate the range of Asian longhorned beetle in the United States. Maps of Asian longhorned beetle host preference across the United States were obtained from the USDA Forest Service (D.J.N., unpublished data). Resultant EI values were used to identify landfills and transport corridors at particularly high risk to potential Asian longhorned beetle establishment (Fig. 3).

Adult Emergence and Reproduction. It is generally recognized that only a fraction of the total Asian longhorned beetle eggs deposited will produce adults. Zhao et al. (1993), for example, found that only 35–37% of eggs laid on *Populus* trees made it to adults in nature. Moreover, some oviposition pits may fail to contain eggs. Zhou et al. (1984), for example, noted that of the 308 egg pits observed, 46 (14.9%) contained no eggs. Emergence, or percentage of Asian longhorned beetle exit sites relative to the total number of oviposition sites, was estimated from infested trees taken from three U.S. sites. 1) We calculated percentage of emergence on maple (*Acer platanoides* L., *A. rubrum* L., *A. saccharum* Marsh., and *A. pseudoplantanus* L.) and elm (*Ulmus pumila* L.) harvested from a stand near Jersey City, NJ, in November 2002. 2) We

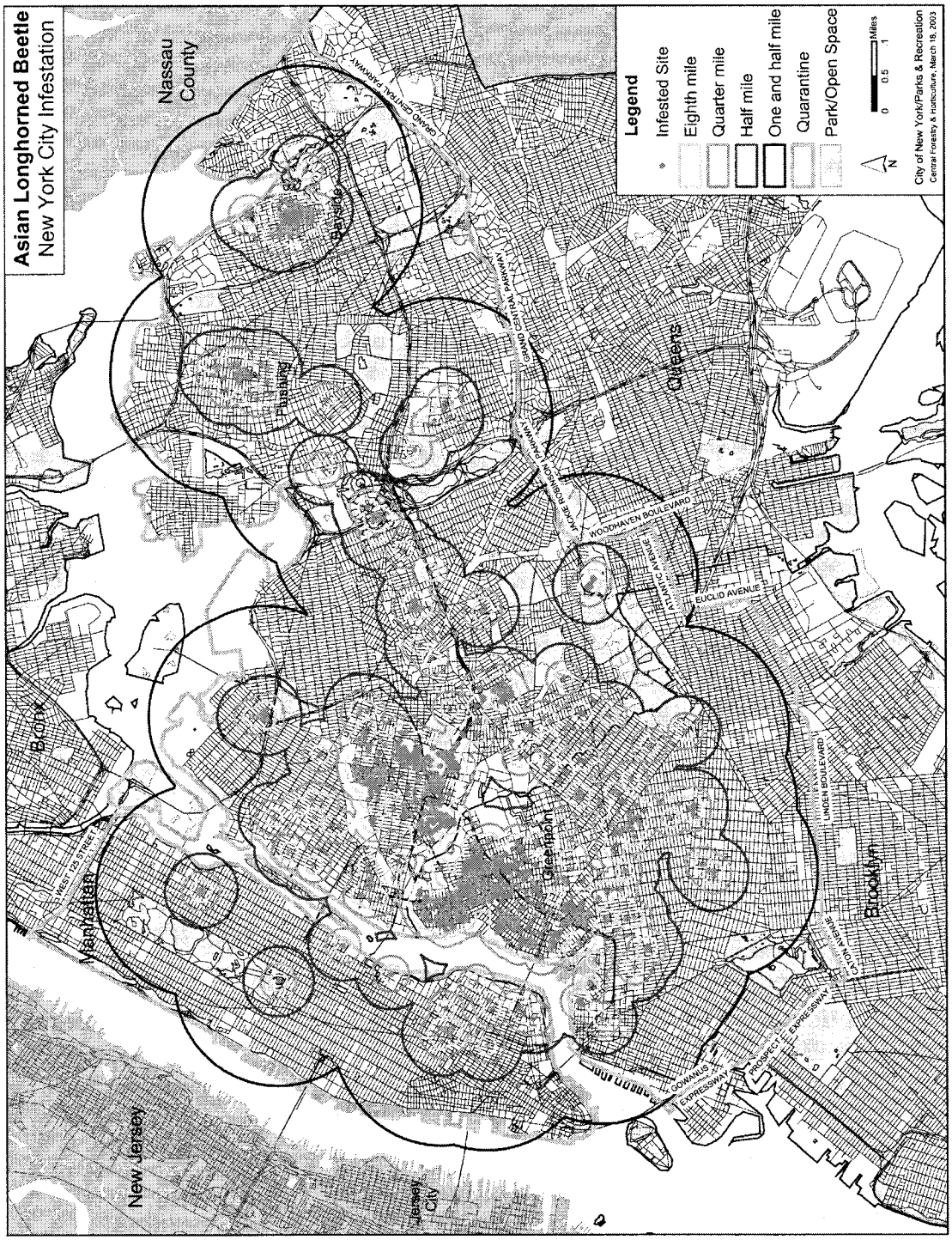

Fig. 2. Asian longhorned beetle quarantine zone in NYC. Figure shows recent infestation areas and calculated concentric circles of 0.2- (eighth mile), 0.4- (quarter mile), 0.8- (half mile), and 2.4-km (one and half mile) radius from points of infestation.

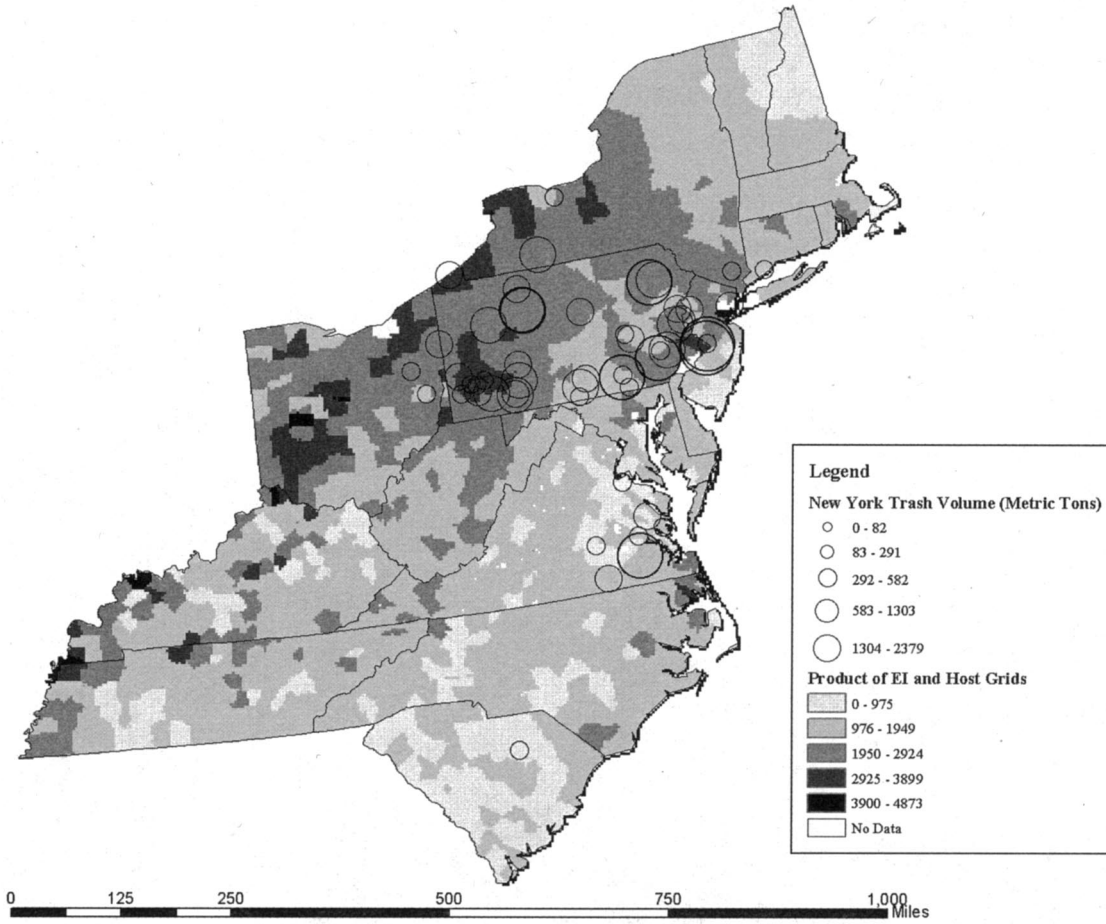

Fig. 3. Location and quantity of municipal solid waste from New York City sent to 56 landfill facilities across the eastern United States since 1997. Sites are superimposed on host-climate county-level map showing the level of risk to Asian longhorned beetle establishment.

estimated emergence on maple (*Acer platanoides, A. pseudoplantanus,* and *A. saccharum*), elm (*Ulmus americana* and *U. pumila*), and willow (*Salix* spp.) logs harvested in New York City (Central Park, Brooklyn, Queens) in late 2002 and early 2003. 3) We also estimated emergence on maple (*Acer saccharum, A. rubrum,* and *A. platanoides*) collected at Bayside, NY, in April 1999. For 2 and 3, logs were incubated in the laboratory at ≈20°C; we assumed the logs represented all of the fresh tree wood weight above ground, at most, 5% on average, and at minimum, 1% of total.

Asian longhorned beetle eggs deposited in the summer and fall typically emerge as adults in the late spring and summer of the following year. To verify the actual seasonal risk of finding Asian longhorned beetle adults on woody debris, we used observed Asian longhorned beetle emergence times based on tree species collected at Bayside. We compared this trend to estimated Asian longhorned beetle emergence based on laboratory incubation data and phenology modeling. Emergence timing was plotted, stratified by 2-wk intervals from June through September.

Asian Longhorned Beetle Beetles per Ton of Wood. The number of Asian longhorned beetle in infested trees was estimated by counting Asian longhorned beetle oviposit and exit sites on 97 trees harvested in November 2002 from an infested maple stand near Jersey City, NJ. The total number of Asian longhorned beetle oviposition and exit sites was assumed to represent a population growth of >4 yr. Tree diameter was used to estimate the fresh or "wet" weight of the tree; this was achieved by using the dry weight biomass allometric equations of Jenkins et al. (2003) and a dry:wet weight ratio of 0.5 (Briggs 1994, Saatchi and Moghaddam 2003).

Asian longhorned beetle rarely occupies the trunk but rather infests branches of the tree crown. One of the most complete data sets on the conversion of tree diameter to biomass in U.S. northern hardwoods is that of Jenkins et al. (2003). Because they did not give an

equation for crown branches, we subtracted estimated foliage plus stem biomass (see Table 6 in Jenkins et al. 2003) from the total aboveground biomass (see Table 4 in Jenkins et al. 2003) to estimate the branch biomass.

The number of beetles per ton was calculated by dividing the number of beetle exit sites in year 4 by the branch (wet weight) biomass of each tree. We assumed that the number of beetle exit sites in year 4 was a fraction of the total number of exit holes cumulated over 4 yr after Asian longhorned beetle establishment and geometric population growth. The total number of beetles per tree was partitioned into year 1, year 2, year 3, and year 4 populations by using a decreasing geometric function; the sum of years 1, 2, and 3 was then subtracted from the total to derive an estimate of the number of exit sites in year 4.

Two independent sets of laboratory data were used to verify the field-derived estimates of the number of beetles per ton of wood. 1) We studied beetle emergence from highly infested portions of selected Asian longhorned beetle-positive maple, elm, and willow trees harvested at seven sites in NYC (Brooklyn, Central Park, and Queens) and Amityville, NY, between April 1999 and February 2002. The infested wood was brought in barrels to the laboratory and incubated at ≈20°C. In total, the 59 barrels, weighing ≈34 kg each, yielded 652 Asian longhorned beetle beetles. 2) We studied emergence rates on 151 maple logs with evidence of Asian longhorned beetle oviposition sites or exit holes that had been collected at Bayside, NY, in April 1999 and then incubated in the laboratory at ≈20°C. For each tree species, the number of male and female beetles to emerge, total exit sites, total oviposition sites, and total log volume were measured. We converted the volume to wood wet weight, assuming a dry-weight wood specific gravity of 0.75 g/ml (Simpson 1993) and a 50% moisture content (Briggs 1994, Saatchi and Moghaddam 2003) and calculated the number of beetles per ton.

Asian Longhorned Beetle Infestation Area. Eradication programs routinely remove the most heavily infested trees from infested areas and survey remaining trees within 0.4 km of known infestations (level 1 areas); additional surveys are made to a distance of 2.4-km radius (level 2 areas). The New York Department of Parks and Recreation developed an updated map of the infested areas in NYC and calculated the area in concentric circles of 0.2-, 0.4-, 0.8-, and 2.4-km radius from points of infestation (Fig. 2). We multiplied the calculated areas within the concentric circles by the estimated Asian longhorned beetle population levels. The latter were estimated using Asian longhorned beetle dispersal numbers as a function of distance (USDA–APHIS 2000). The products, weighted area estimates of Asian longhorned beetle populations in the increasing circle sizes, were then expressed as fractions of the total area of NYC.

NYC Street Tree and Forest Surveys. A total tree count (498,470 trees), recorded by tree species, had been made along streets in a 1995–1996 census of the five NYC boroughs (Bronx, Brooklyn, Manhattan, Queens, and Staten Island) (NYDOS 1996). The number of nonstreet trees by tree species was available from a USDA Forest Service 1995–1996 sampling of off-street forested and "backyard" locations in the five boroughs (D.J.N., unpublished data).

NYC Storm Type and Frequency. The timing of storm events reported in Queens County, New York, between 1 January 1950 and 28 February 2003 was accessed from NCDC (2003). These events included coastal storm, drought, excessive heat, flash floods, floods (coastal/urban/stream flooding), hail, heavy rain, heavy snow, high wind, lightning, rip currents, snow and ice storms, thunderstorm (and wind speed), tornado, wind, and winter storms (NCDC 2003). The number of events was plotted by month and compared with the number of emergent Asian longhorned beetle and to the levels of woody debris collected curbside.

Pathway Analysis

We used traditional pathway analysis (Palisade Corporation 2003) to estimate the probability that waste wood within the NYC quarantined area is a regulatory risk to areas receiving this material. Pathway analysis relies on an accurate definition of points (or steps) on a trajectory of pest movement from source to destination. Each point involves a critical change in the presence of the pest, typically a reduction in the probability of its continued transfer along the pathway conditioned by either its biology or a management intervention. We defined 11 steps on the wastestream from curbside to landfill and quantified the likelihood of beetles surviving each step (Table 1). In all steps, the *RiskPert* (*mn, ml, mx*) probability distribution function was used. The *Pert* distribution is a special form of the beta distribution and is defined by minimum, most likely, and maximum values. For example, *Pert* (*0, 2, 10*) specifies a beta distribution with a minimum of 0, a maximum of 10, and a most likely value of 2. Compared with a triangular distribution, the *Pert* distribution places more likelihood in the central tendencies of the distribution and reduces emphasis on the trailing ends of the distribution.

After quantifying each step in the pathway, a stochastic model was constructed using Excel (Microsoft Corporation 2000) and @RISK (Palisade Corporation 2003). The annual number of viable beetles reaching landfills was the mathematical product of the distributions representing the 11 steps on the pathway (see equations in Table 1).

We ran 10,000 Montecarlo iterations of the model to calculate for the emergent period: 1) the annual number of beetles sent to landfills, 2) the annual number of beetles reaching any one landfill, and 3) the annual number of beetles crawling to the surface of any one landfill. The final statistic was an estimate of the probability that a mated female Asian longhorned beetle would survive transport, disposal, and burial. The probability of any two Asian longhorned beetle mating or the mated pair probability function was expressed as $p = (1 - e^{-X/2})^2$, where X is the number of beetles (Vail et al. 1994). Equations used are presented in Table 1.

Table 1. Scenario A: Pathway steps 1 through 11 of @ RISK pathway analysis of business-as-usual collection and disposal practices

Step	Pathway parameter	Minimum	Most likely	Maximum	Expected value	Derived pathway parameter	Mean	5% tile	50% tile	95% tile	Mode
P1	Tons of MSW picked up in NYC per year	2235590	2353370	2582940	2372002	Tons of MSW picked up in NYC per year (P1)	2372002	2274446	2367605	2484590	2354271
P2	Proportion of annual MSW picked up in emergent period (June - Sept)				0.34	Tons of MSW picked up in NYC in emergent period (June - Sept) (P1*P2)	806481	773312	804986	844761	800452
P3	Proportion of NYC MSW from infested locales	10.01%	10.17%	10.80%	0.103	Tons of NYC MSW from infested locales per emergent period (P1*P2*P3)	82651	78819	82501	86999	81586
P4	Proportion of MSW that is wood in emergent period	0.79%	1.86%	2.86%	0.019	Tons of MSW that is wood per emergent period (P1*P2*P3*P4)	1528	989	1529	2058	1423
P5	Proportion of wood that is host material	13.50%	27.80%	42.10%	0.278	Tons of host material wood in MSW per emergent period (P1*P2*P3*P4*P5)	425	237	414	648	416
P6	Proportion of host material wood that is infested	0.06%	0.41%	0.76%	0.004	Tons of infested host material wood per emergent period (P1*P2*P3*P4*P5*P6)	1.74	0.67	1.63	3.2	1.32
P7	Proportion wood sent to landfill	71.10%	80.30%	100.00%	0.821	Tons of infested wood sent to landfills per emergent period (P1*P2*P3*P4*P5*P6*P7)	1.43	0.55	1.33	2.63	1.18
P8	Proportion of infested wood in adult stage when picked up	1.93%	2.41%	2.89%	0.024	Annual tons of infested wood in adult stage when picked up and sent to landfill (P1*P2*P3*P4*P5*P6*P7*P8)	0.034	0.013	0.032	0.063	0.031
P9	Beetles per ton of infested wood	2.7	17.9	435.4	85.2	Number of beetles sent to landfills per emergent period, X1 (P1*P2*P3*P4*P5*P6*P7*P8*P9)	2.934	0.257	2.078	8.394	0.244
P10	Proportion of beetles sent to any one landfill	0.00%	0.01%	0.05%	0.0001	Annual number of beetles sent to any one landfill, X2 (P1*P2*P3*P4*P5*P6*P7*P8*P9*P10)	4.30E-04	2.09E-05	2.33E-04	1.47E-03	4.03E-05
P11	Proportion of surviving adults crawling to surface of landfill	0.00%	0.10%	3.00%	0.0057	Annual number of beetles crawling to the surface of any one landfill, X3 (P1*P2*P3*P4*P5*P6*P7*P8*P9*P10*P11)	2.45E-06	3.79E-08	9.15E-07	9.81E-06	1.84E-08

	Pathway parameter	Expected value	Equations	Mean	5% tile	50% tile	95% tile	Mode
a_p	Probability of a mated pair given number of beetles sent to landfills in emergent period	0.59206182	$a_p = (1-e^{-X1/2})^2$	4.53E-01	1.46E-02	4.18E-01	9.70E-01	4.16E-03
a_y	Years until a mated pair given number of beetles sent to landfills in emergent period	1	$a_y = RiskGeometric\ (a_p)$	1.77E+01	0.00E+00	1.00E+00	5.30E+01	0.00E+00
b_p	Probability of a mated pair given annual number of beetles sent to any one landfill	4.5305E-08	$b_p = (1-e^{-X2/2})^2$	1.24E-07	1.10E-10	1.36E-08	5.37E-07	4.89E-12
b_y	Years until a mated pair given annual number of beetles sent to any one landfill	22,072,833	$b_y = RiskGeometric\ (b_p)$	8.83E+09	5.31E+05	4.60E+07	7.55E+09	2.81E+05
c_p	Probability of a mated pair given annual number of beetles crawling to the surface of any one landfill	1.4551E-12	$c_p = (1-e^{-X3/2})^2$	6.59E-12	3.59E-16	2.09E-13	2.40E-11	4.54E-18
c_y	Years until a mated pair given annual number of beetles crawling to the surface of any one landfill	6.8724E+11	$c_y = RiskGeometric\ (c_p)$	3.30E+14	1.48E+10	2.87E+12	2.68E+15	n/a

All probability distributions based on RiskPert (min,ml,max) equation (Palisade Corporation 2003). Equations for the probability of a mated pair (a_p, b_p, c_p) and years for this to occur (a_y, b_y, c_y) are given, where RiskGeometric (x) is the geometric probability distribution (Palisade Corporation 2003).

Scenarios Evaluated

A set of four test and three management scenarios were analyzed. The test scenarios were as follows: scenario A, business-as-usual, "baseline" or most common practices of collection and disposal; scenario B, effect of using a single (mega) landfill; scenario C, effect of severe storm in which all woody debris was sent to one landfill; scenario D, effect of illegal dumping of 1% of the city's waste. Scenarios A–D were a set of alternative waste disposal practices or situations encountered by NYC. The three management scenarios included scenario E, separate collection of wood at curbside across all NYC (the 311 System); scenario F, same as scenario E but collection was limited (in time and location) to known emergence period and to infestation areas only; and scenario G, intensified Asian longhorned beetle detection and eradication.

Scenario A, Most Common Collection and Disposal Practice. The 11 steps defined along the pathway involved the following calculations.

Step 1. Total Tons of Residential + Institutional MSW Picked Up in NYC per Year (P1). The mean (2,353,370 tons of MSW per year) was the 1996–2000 average, the minimum (2,235,590 tons of MSW per year) was the 1998 value, and the maximum (2,582,940 tons of MSW per year) was the 2000 value (NYDOS 2001).

Step 2. Proportion of Annual MSW Picked Up 15 June to 30 September (P2). The Asian longhorned beetle emergent period was estimated to be from 15 June to 30 September; this was 121 d or 0.34 of the year (no minimum or maximum calculated for this parameter).

Step 3. Proportion of MSW from Infested Locales (P3). The mean (10.17%) was the weighted real estimate of infestation locales, expressed as a fraction of the total NYC area. The minimum (10.01%) was based on the assumption that virtually all Asian longhorned beetle had dispersed to within a 0.8-km distance. The maximum (10.80%) was based on the assumption that detection surveys over 0.8- to 2.4-km distances were incomplete and that additional infested trees would be found. Instead of the 0.41% infestation level, it was posited that 5% of all Asian longhorned beetle detected would be found in this zone when complete surveys were available.

Step 4. Proportion of MSW that is Woody Debris in 15 June to 30 September Period (P4). Analysis of the SCS Engineers (1992) seasonal (winter, spring, summer, and fall) breakout of woody debris was plotted on an annual distribution curve. The proportion in the 15 June to 30 September period (1.86%) was almost double of the four-season average (1.11%). The minimum (0.79%) and maximum (2.86%) were the ranges of woody debris categories sampled by the city (SCS Engineers 1992).

Step 5. Proportion of Wood That is Host Material (P5). The mean (27.8%) was the fraction of woody debris of live, preferred host tree species in the >1.3-cm-diameter size class found at curbside in the pass-through survey. The maximum (42.1%) was the value for live + dead woody debris, assuming that all could be live material. The minimum (13.5%) was set to represent a symmetrical distribution about the mean (R.J.M., unpublished data).

Step 6. Proportion of Host Material Wood that is Infested (P6). The fraction of the trees in the NYC quarantine zone infested was estimated, on the basis of 2002 field surveys to be 0.41%. The minimum (0.06%) was based on Manhattan only. The maximum (0.76%) was set to represent a symmetrical distribution about the mean.

Step 7. Proportion Wood Sent to Landfill (P7). MSW sent to American Ref-Fuel, Inc., facilities was incinerated. We calculated the tons MSW sent to these facilities in 2002–2003 (19.7%) and used this to determine the remaining fraction (80.3%) sent to landfills. The minimum was estimated by Themelis et al. (2002), 71.1%. The maximum (100%) assumed no incineration or recycling.

Step 8. Proportion of Infested Wood with Adults Present in Wood Upon Pick Up (P8). We estimated that a small fraction (2.41%) of the total Asian longhorned beetle population in any one collection is an adult that has not yet emerged from the wood when picked up at curbside in the emergent period (15 June–30 September). This was based on an average of 41.5 waste collections over the 121-d emergent period; that is, 1/41.5 of the total number of emergent Asian longhorned beetle will be in any one collection. The minimum (1.93%) and the maximum (2.89%) were similarly calculated based on the minimum and maximum number of collections.

Step 9. Beetles per Ton of Infested Wood (P9). The mean number of Asian longhorned beetle per ton of wood (18.3 beetles) was estimated from the Jersey City field data on number of exit holes per estimated fresh (wet) weight of the tree crown, i.e., branch component. The minimum (2.7 beetles) and the maximum (435.45 beetles) were based on the same data set.

Step 10. Proportion of Beetles Sent to Any One Landfill (P10). The mean (0.01%) was the fraction of the 1.62 tons of wood per day average with emergent Asian longhorned beetle of the 19958 tons of MSW per day NYC sent to the entire complement of 56 landfill sites. The minimum (0.0003%) was the fraction sent to the smallest active landfill (Maplewood Recycling and Disposal Facility, Amelia, VA; 13.6 tons of MSW per day), and the maximum (0.05%) the fraction sent to the largest landfill (GROWS Landfill, Morrisville, PA; 2378.6 tons of MSW per day).

Step 11. Proportion of Surviving Adults Crawling to Surface of Landfill (P11). There was no observational data on this parameter. Preliminary experiments where beetles were buried under 15.2 cm of uncompacted soil indicated that few if any of the beetles would be able to emerge and those that could emerge would likely be in poor condition (M. Keena and D. Lance, unpublished data). We arbitrarily set the minimum, mean, and maximum escape rates to be 0, 1, and 30%, respectively. Given that up to 12 sixty-centimeter lifts of MSW were layered over one another on the active landfill area, we considered that only the last lift posed any likelihood of Asian longhorned beetle es-

cape. Assuming an average of 10 lifts before capping at day's end, we divided the minimum, mean and maximum values by 10 and used 0.0, 0.1, and 3.0%.

Scenario B, One Mega Landfill. A policy change creating a single one landfill facility for all the City's MSW was achieved by altering step 10 to have a minimum, mean, and maximum of 100%.

Scenario C, Major Summer Wind-Storm Event. Severe storm events in NYC are an important mechanism generating woody debris. We posited that woody debris equivalent to the wood tonnage normally collected at curbside over the emergent period fell in a single storm. We also assumed that this was disposed of in a brief collection interval at a single landfill facility. To achieve this, we set the minimum, mean, and maximum values of step 10 at 100%.

Scenario D, Illegal Dumping. If illegal dumping of MSW were to occur (NYDOS 2003b), it would pose a very high risk of Asian longhorned beetle escape. We posited a situation in which illegal dumping equivalent of 1% of total annual woody debris occurred at 10 different, unmanaged, nonlandfill sites. To examine this variant, the following occurred. 1) Step 2 was deleted. We assumed that MSW at all seasons contained live Asian longhorned beetle (at some stage of development) that could emerge as reproductive adults. 2) Step 11 was assigned a fraction of 100% to the minimum, mean, and maximum. We envisioned that, unlike a managed landfill with daily covering of the waste, there would be no effective barriers to deter the Asian longhorned beetle from escaping the illegally dumped MSW. Two new steps were added: 3) step 6 (proportion of wood sent to landfills that is illegally dumped) was inserted (after proportion wood sent to landfill). We arbitrarily assigned an estimate of 1% (no minimum or maximum entered); and 4) step 9 (proportion of beetles sent to any one illegal dump site) was inserted (after beetles per ton of infested wood). We arbitrarily assigned an estimate of 10% (no minimum or maximum entered).

Management Options. Scenarios E–G comprised a set of practical alternatives seriously considered for deployment by NYC. The model outputs were discussed with sanitation staff and Asian longhorned beetle eradication experts as a means of assessing the feasibility, effectiveness, and, where economic data are available, the cost of each option.

Sensitivity Analysis

@RISK generated a table of parameter sensitivities for each scenario. Sensitivity was estimated by the regression coefficient, and by the correlation between a given parameter on the pathway and the final parameter in the @RISK model, namely, the proportion of surviving adults crawling to the surface of the landfill. In addition to sensitivity analysis using the regular @RISK routines (Palisade Corporation 2003), we ran @RISK Professional and Industrial's Advanced Sensitivity Analysis (Palisade Corporation 2002) on scenario A. This provided a means of verifying and extending the scope of the original analysis. We ran the advanced sensitivity analysis using the percentile distribution step-type in increments of 1, 5, 25, 50, 75, 95, and 99%.

Ten-Year Projected Costs of 311 System

We projected the costs to NYC of the 311 System over the coming decade, 2004–2013 by using the Office of Budget and Management (USOBM 2004) guidelines on procedure and estimated rates of inflation. The latter is the rate of increase in the U.S. Gross Domestic Product deflator from the Administration's economic assumptions. The annual rates in 2005 (1.9%), 2006 (2.0%), 2007 and 2008 (2.1%) varied but remained constant for the sixth through 10th year (2009–2013) of the budget forecast (USOBM 2004). We used the Office of Budget and Management rates, but adjusted these by NYC forecasts, given that the city's costs are nearly double the national average and the second highest in the United States (Malanga 2002). The projected annual inflation rate for NYC over the 2003 though 2007 period was 2.5%. Based on actual cost increases in the city's budget from 1994 through 2004, the projected annual cost rate increase was 3.65% (McMahon 2004). Ratios between NYC projected 4-yr annual inflation rate, the city's 10-yr actual cost increases, and the U.S. Office of Management and Budget annual fiscal year 2005 though 2013 national average rate were determined and applied annually to lower ($6.1 million) and upper ($9.1 million) range cost estimates of curbside waste wood collection.

Results and Discussion

Description of the Pathway

MSW and Woody Debris. The annual tons of MSW in NYC increased only slightly from 1990 to spring 2003. In the early 1990s, ≈80% of MSW had been disposed at Fresh Kills, the remainder being incinerated. Disposal of the City's MSW at sites outside NYC increased markedly after 1996 (Fig. 1). We estimated that of the total 32.4 million tons of MSW (1990–2003), 12.9 million tons of the city's MSW has been disposed in landfills outside the city's quarantine zone. Half of this number, or 6.4 million tons, was residential + institutional MSW.

From 1996 to 2000, an average of 2.4 million tons of residential + institutional MSW was collected per year, of which 0.45 million tons per year was incinerated (NYDOS 2001). Our estimate of the fraction of woody debris in the NYC wastestream (1.1%) was half that of Themelis et al. (2002); their estimate (2.2%) included processed wood such as lumber and plywood, and commercial MSW.

Asian Longhorned Beetle in the Wastestream. There were potentially thousands of Asian longhorned beetle in the NYC wastestream that could be transported to landfills outside the city. We estimated, for example, that had all woody debris in residential + institutional MSW in the infested locales (Level 1 core

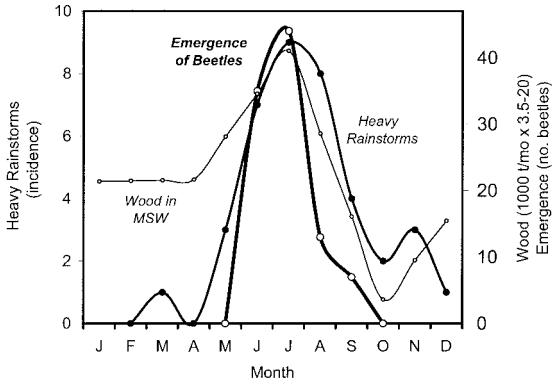

Fig. 4. Incidence of heavy rainstorms versus the seasonal distribution of woody debris and emergence of Asian longhorned beetle.

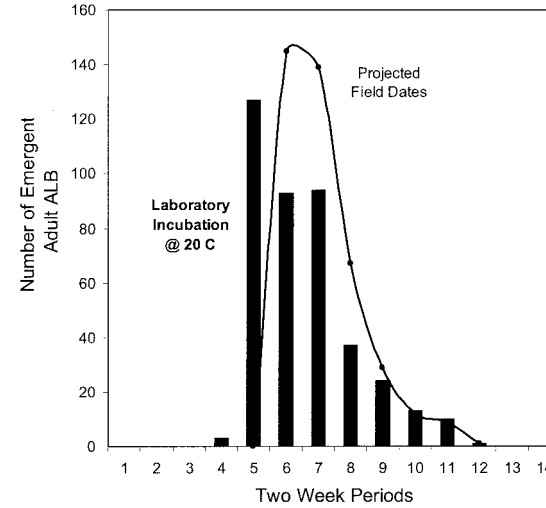

Fig. 5. Seasonal incidence of number of adult Asian longhorned beetles emerging under laboratory incubation at 20°C versus emerging in field under natural conditions.

area) contained the beetle at the rate of 18.3 Asian longhorned beetles per ton of wood, 52,392 would have been in waste collected at curbside. This potential number, however, decreased to a tiny fraction (0.000005 Asian longhorned beetle) as other factors were considered, such as the fraction of woody debris that was of preferred host species (0.278), the fraction of preferred host species that was actually infested (0.004), picked up in the emergent period (0.340) with emergent Asian longhorned beetle adults (0.024), and sent to landfills rather than incinerated (0.801), to end up on any one day at one of the 56 landfills (0.0001). Fewer yet would escape burial and form a mated pair (Table 1).

Seasonal Changes in Asian Longhorned Beetle. There was a strong peak in severe storms in the NYC area in July and August. Heavy rainstorms were an important mechanism of branch fall, as shown by the coincident rise in woody debris put out for collection (Fig. 4). The quantity of total MSW showed relatively high levels over the late spring, summer, and early fall, with peaks in May and October at the time of leaf collection. By comparison, the levels of woody debris in MSW peaked strongly in July and were notably low in October. Overall, the summer woody debris level was about twice the annual average (1.86 versus 1.11%).

The striking coincidence of Asian longhorned beetle emergence with the peak of woody debris put out for collection (Fig. 4) was important because it increased the likelihood of Asian longhorned beetle reproduction as seasonally elevated levels of woody debris entered the wastestream.

Several researchers have noted a consistently strong peak of Asian longhorned beetle emergence in the early summer. In our infested-log incubations, the majority of Asian longhorned beetle emerged within June and July. Figure 5 demonstrated that it took 6–8 wk after bringing logs into the laboratory in April before the first adult Asian longhorned beetle emerged. These logs were held at a constant 20°C, which was warmer than the average NYC April temperatures, and warmer than the average daily temperatures for many days in May. Hence, compared with laboratory observations, emergence of Asian longhorned beetle in the field was delayed by at least a month—a fact consistent with the record of first beetle finds in NYC over the period 26 June–29 July 2003 (W.J.N., unpublished data). Emergence in the field was more synchronized, possibly due to average temperatures in June and July being typically higher than 20°C used in the laboratory. The main body of the curve represented emergent larvae that had been near pupation at the time of the fall/winter chill. Records on dates of first sightings (W.J.N., unpublished data) suggested ≈1,100 growing degree-days (°C) was required for Asian longhorned beetle emergence. The long tail of the distribution (Fig. 5) represented larvae that took longer to complete their development.

In brief, temperature variation was shown to exert a large influence on actual timing of Asian longhorned beetle emergence (and hence, of the risk of reproductive Asian longhorned beetle occurring in the wastestream). Early springs and late falls shifted the actual tails of the distribution. For our purposes, we effectively limited Asian longhorned beetle emergence to 15 June to 30 September or to about one-third (34%) of the year.

Number of Asian Longhorned Beetles per Ton of Wood. Infested trees contained 18.3 (6.4 SEM) viable Asian longhorned beetles per ton of branch wood, based on infested trees harvested at Jersey City. The two laboratory incubation studies of highly infested branches and trunks harvested resulted in estimates of 423.3 and 378.1 Asian longhorned beetles per ton. This was close to the maximum value (435.4 Asian longhorned beetles per ton) derived in field estimates based on complete trees harvested at Jersey City. If we assumed that the selected samples of highly infested branches and trunks brought to the laboratory were in

the uppermost 5% of infestation density, the adjusted values were then 21.2 and 19.5 Asian longhorned beetle per ton. The estimates were close to the 18.3 Asian longhorned beetle per ton of the field estimate, but they provided only broad approximations, given there was no way to reconstruct the original full tree weights of logs sent to the laboratory.

A conspicuous feature of the field (Jersey City) estimates of Asian longhorned beetle per ton was a high standard error of the mean. Part of this is attributed to the presence of a few trees with very high numbers of beetles present. Heavily infested trees probably had been used by the beetles for multiple generations, whereas others may have been infested only recently. There were also differences between tree species and trees used as oviposit sites.

Percentage of Asian Longhorned Beetle Emergence from Wood. Not all Asian longhorned beetle eggs oviposited on trees successfully emerged as adults. We estimated that on average, only one in 12 eggs (8.2%) emerged from infested trees harvested at Jersey City. Of five tree species in his study, red maple had by far the highest percentage of emergence (25.9%); Norway and sycamore maples were moderate by comparison (7.4%).

The laboratory incubation studies of the NYC trees estimated that on average, one in eight (12.3%) eggs oviposited emerged as adults; emergence in horse chestnut (7.9%) was one-half compared with emergence (15.0%) in white willow. We estimated one in five (19.9%) eggs emerged from trees of three species harvested at Bayside, NYC.

Landfills as Effective Asian Longhorned Beetle Burial Sites. Landfill sites contracted by NYC were all closely monitored under federal (U.S. Environmental Protection Agency) and state (Department of Environment) regulations. Inspections for compliance were as frequent as twice per week. Typically, the total area active in the landfill during any one day was <1 ha (of a total area of 20–40 ha). During the day, up to 12 lifts each 60 cm in thickness may be placed sequentially one over another on a limited area. At the end of each day, a 15-cm layer of heavy soil or mining spoil is spread by bulldozer, and then compacted by a steamroller with a cleated drum to achieve a hardened surface capable of holding 19-ton trucks the next day. If the active area is going to be unused for an interim period (e.g., 1 mo), it is covered with 30 cm of soil and compacted. When a disposal site was completely filled, it was covered by a synthetic plastic covering, a 60-cm layer of top soil was added, and it was revegetated in grass.

In the preliminary studies on the capacity of Asian longhorned beetle to emerge from burial in lightly compacted soil, results indicated that beetles would attempt to dig out but that they were weakened in the process. From this we concluded that 1) few if any beetles would be able to dig out and most beetles subjected to the rigors of collection, waste yarding, compression, transport, and burial at a landfill are likely to perish. There was clearly no guarantee that 100% would fail to reach the surface. We judged, however, that it would be very unlikely that Asian longhorned beetle would escape once buried under one or more lifts and a 15 cm top layer of heavily compacted soil. 2) Asian longhorned beetle was unlikely to survive >2 wk under soil at 20°C; higher temperatures and prolonged periods of exertion without food are likely to shorten survival.

More than 95% of MSW was transported to landfills in trucks as compacted but unsealed waste (Themelis et al. 2002). Although a tarpaulin is placed over the load, the care and consistency with which is kept tight were not examined in this study. There was a need for better information on the potential for Asian longhorned beetle reproduction and the escape of gravid females during transport and dumping.

The risk of establishment was increased by the location of disposal sites in geographic areas with a highly suitable climate and vegetation host type. The host–climate suitability map (Fig. 3) indicated that landfills in the northern one-half of Pennsylvania, southern and western New York, and eastern Ohio were in areas moderately to highly favorable to Asian longhorned beetle establishment. Forest cover types in these areas contained >40% (on a scale of 0–100) of preferred host tree species and received the bulk of the MSW from NYC. Forests in southern Pennsylvania, Virginia, and South Carolina had a lower host rating (0–40% preferred host species; D.J.N., unpublished data), but all disposal sites had medium-to-high climatic suitability. The ecoclimatic index rated high (50–75 on a scale of 0–75) in all states with landfills used by NYC. The transportation corridors to the landfill sites in Pennsylvania, New York, and Ohio also were through forested vegetation and climates moderately to highly suitable to Asian longhorned beetle growth. Corridors south through Virginia and South Carolina were at low to slight risk levels of host–climate suitability (Fig. 3).

Pathway Analysis

Risk of Asian Longhorned Beetle Escape and Establishment. We were able to estimate and characterize marked reductions in the number of viable Asian longhorned beetle at each of the steps along the pathway from curbside to landfill (Fig. 6).

The pathway analysis of practices routinely used by the City of New York to dispose of its MSW (scenario A) indicated a moderate probability ($P = 0.45$) that a mated pair would be sent to landfill (i.e., the 56 landfills collectively) within the same year. The probability of a mated pair being sent to any one landfill was small ($P = 0.00000012$), and the likelihood of a mated pair crawling to the surface at any one landfill was very low ($P = 0.0000000000066$). The time required for a mated pair to arrive at any one landfill and escape burial was estimated to be 330 trillion years (Tables 1 and 2).

A test of the effect of sending all MSW to one mega landfill (scenario B) showed the importance of dispersing MSW among many landfill sites, as has been the practice of NYC in the recent past. The analysis

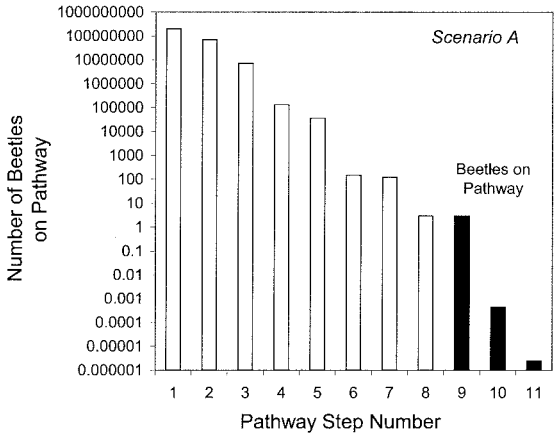

Fig. 6. Potential number of Asian longhorned beetle on pathway based on @RISK analysis of most common practices variant scenario A. Pathway steps 1–8 contain *potential* numbers of beetles had all wood in MSW been infested. Steps 9–11 are actual simulated estimates of Asian longhorned beetle in infested wood.

indicated that the probability of a mated pair crawling to the surface was increased 32 million-fold (from $P =$ 0.0000000000066 in scenario A to 0.00021). The time required for a mated pair to arrive at the mega landfill and escape burial was estimated to be 1.2 trillion years (Table 2).

Our results supported the need for special attention to storm events. Scenario C showed that the likelihood of a mated pair escaping burial was relatively high ($P =$ 0.013); in fact, 2.0 billion-fold higher than the most common practices (scenario A). It was shown that the escape of an Asian longhorned beetle mated pair would likely happen within 3.3 million years (Table 2).

Illegal dumping (scenario D) was initially thought to represent by far the worse-case situation because emerging Asian longhorned beetle within the woody debris would not encounter any obstacles to escape and establishment. Our results indicated the probability of a mated pair escaping burial at one dump site was 0.017, or 2.6 billion-fold more than business and usual (scenario A) but only about double (1.31-fold greater) that of the severe storm variant (scenario C); it was estimated that it would take 3,499 yr for this to occur (Table 2).

Scenario Evaluation. Given that the risk of routine collection and disposal was virtually nil, there was no expectation that a separate curbside collection and chipping of wood waste (scenario E) would significantly increase the safety margin of containment.

The cost of targeted collection (scenario F), based on the fraction of MSW collection within the 121-d Asian longhorned beetle emergence period (0.34 of year) and limited to level 1 and level 2 infestation locales (≈83% of NYC area), was estimated to cost ≈$1.7 to $2.6 million per year, compared with $6.1 to $9.1 million per year to fully implement the 311 System. The cost based on the emergent period of 121 d (34% of year) and level 1 area only (20.2%) was ≈$0.4

Table 2. @RISK probability analysis (Palisade Corporation 2003) for four scenario variants of New York City municipal solid waste collection and disposal practices

Variant of disposal practices	Scenario A, Most common practices	Scenario B, single mega-landfill	Scenario C, extreme storm	Scenario D, illegal dumping
Parameter		Probability		
Probability of a mated pair given no. of beetles sent to landfills per emergent period or emerging from illegally dumped wood per year	0.45	0.45	0.94	0.36
Probability of a mated pair given annual no. of beetles sent to any one landfill or illegal dumpsite	0.00000012	0.45	0.94	0.017
Probability of a mated pair given annual no. of beetles crawling to the surface of any one landfill or illegal dumpsite	0.0000000000066	0.00021	0.013	0.017
Parameter		Year		
Years until a mated pair given no. of beetles sent to landfills per emergent period or emerging from illegally dumped wood per year	18	21	0.22	37
Years until a mated pair given annual no. of beetles sent to any one landfill or illegal dumpsite	8,833,577,614	21	0.24	3,349
Years until a mated pair given annual no. of beetles crawling to the surface of any one landfill or illegal dumpsite	330,119,044,822,977	1,261,283,373	3,299,262	3,499

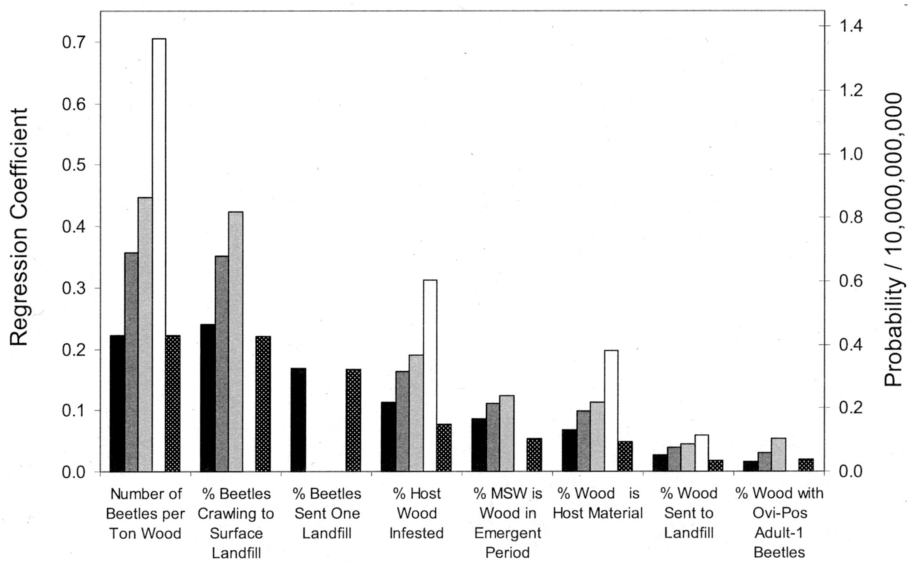

Fig. 7. @RISK sensitivity analyses. Parameters ranked by strength of regression coefficient based on the regular @RISK sensitivity analysis. Scenarios include A, common practices (black); B, mega landfill (medium gray); C, severe storm (light gray); and D, illegal dumping (white). Some parameters did not apply to all scenarios. The @RISK advanced sensitivity analysis of scenario A (black stippled bar, units on right axis) is scaled so that it has the same proportion as scenario A of regular sensitivity analysis on the left axis.

to $0.6 million per year. These obviously simple calculations served to demonstrate approaches to reduce the cost of separate collection of curbside wood waste by being selective.

If the choice was to apply $6.1 to $9.1 million per year for a separate collection of wood waste, and these funds were obtained from the existing program (≈$10.9 million per year for NYC in 2004) on Asian longhorned beetle eradication (scenario G), the expected impact would be to increase the likelihood of Asian longhorned beetle in woody debris. The fact that by far the most sensitive parameter affecting the risk of Asian longhorned beetle escaping from landfill sites was the number of beetles per ton (Fig. 7), there was strong justification in the added efforts to ensure Asian longhorned beetle populations were further reduced and remain at low levels.

The projected costs of the basic and full services 311 System over the 2004–2013 decade varied from $74.9 to $81.8 million at an annual 2.5% inflation rate, and more realistically, $111.8 to $122.1 million based on the 3.65% increase in the city's actual operation costs experienced over the previous decade.

Sensitivity Analysis. The regular sensitivity analysis of scenario A indicated three parameters, in particular, influenced the probability of a mated pair crawling to the surface of any one landfill, namely, the number of beetles per ton of woody debris (r_g = 0.222), the proportion of surviving adults crawling to surface of landfill (r_g = 0.240), and the proportion of beetles sent to any one landfill (r_g = 0.169). The advanced sensitivity analysis of scenario A resulted in similar results (Fig. 7).

The sensitivity analysis of scenarios B–D also resulted in a sequence of parameters similar to that of scenario A. The implication was that the top three parameters represent effective points for management intervention to reduce the risk of Asian longhorned beetle establishment at the landfills. The parameters least likely to be effective intervention points (not shown in Fig. 7) included the proportion of MSW from high infestation locales in NYC, tons of MSW picked up in NYC in the emergent period, and the proportion of annual MSW picked up in the June-to-September interval.

General Discussion

There was a need for notably better information in three areas: the potential for Asian longhorned beetle reproduction and the escape of gravid females during transport and dumping, the vulnerability of Asian longhorned beetle adults to damage upon compaction of the waste, and the effectiveness of the soil capping at the landfill in preventing Asian longhorned beetle escape.

Although the risk of a single mated pair of Asian longhorned beetle escaping burial under normal disposal practices was extremely low, this was true only as long as exceptions did not intervene. A policy change creating one mega landfill site, or a severe storm that forced the disposal to one landfill, increased the risk of Asian longhorned beetle escape/establishment many millionfold (46 million- and 4.3 billion-fold, respectively) as did the illegal dumping of as little as 1% of the city's annual waste (7.3 billion-fold in-

crease). We also noted that there may be justification for applying the 311 System to level 1 areas (0.4 km from infested trees) in cases where the infestation intensity flared up.

An increased effort toward detection and eradication (scenario G) also was supported by the sensitivity analyses. The most effective management interventions were likely control and eradication (i.e., lower the number of beetles per ton), diversification of landfills (i.e., lower the percentage of beetles sent to any one landfill), and consistent compaction of the garbage lifts and soil covering at the landfill site (i.e., limit ability of Asian longhorned beetle to crawl to landfill surface).

In conclusion, pathway and sensitivity analyses indicated the following: 1) The risk of a single mated pair of Asian longhorned beetle escaping and establishing, under routine collection and disposal practices, was nil. Business-as-usual practices (scenario A) do not pose a large or unreasonable level of risk involving the spread of Asian longhorned beetle to landfill sites. 2) A policy change creating one mega landfill site (scenario B), or a severe storm that forced the disposal of large amounts of woody debris to one landfill (scenario C), increased the risk of Asian longhorned beetle escape/establishment severalfold. Illegal dumping, of as little as 1% of the NYC's annual waste at unmanaged, nonlandfill sites, had even a greater effect (scenario D). 3) Given that routine practices used by the city resulted in very low risk of Asian longhorned beetle establishment, it was not clear that any benefit (i.e., added risk reduction) would result from fully implementing the 311 System (scenario E). Had our analysis shown that routine collection and disposal were high risk (which it was not), there may have been justification for a separate collection of woody debris to provide additional security. 4) The sensitivity analysis indicated that one of the most important parameters influencing the probability of a mated pair crawling to the landfill surface was the number of beetles per ton of wood. This favored the continued and/or increased control and eradication of the Asian longhorned beetle in the quarantine zone (scenario G). 5) Sensitivity analysis also supported the careful monitoring of soil covering and compaction at the landfill to limit ability of Asian longhorned beetle to escape burial, and diversification of landfills (i.e., lower the percentage of beetles sent to any one landfill). Managers need to be cognizant of the fact that dispersion of the waste among a large number of landfill sites is an important factor in reducing the likelihood of Asian longhorned beetle establishment. 7) Potential future applications of the Asian longhorned beetle pathway model include design of targeted detection surveys by using a risk ranking of landfill sites, optimization of waste collection and disposal alternatives by using (re)analysis of parameter sensitivity, application to other areas of Asian longhorned beetle infestation (e.g., Chicago, IL, and Toronto, Canada), and application to other pathways (e.g., firewood) and to other pests (e.g., *Agrilus planipennis* Fairmaire).

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