Effects of Chipping, Grinding, and Heat on Survival of Emerald Ash Borer, *Agrilus planipennis* (Coleoptera: Buprestidae), in Chips

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ABSTRACT The emerald ash borer, *Agrilus planipennis* Fairmaire (Coleoptera: Buprestidae), a phloem-feeding insect from Asia, was identified in 2002 as the cause of widespread ash (*Fraxinus* sp.) mortality in southeastern Michigan and Essex County, Ontario. Most larvae overwinter as nonfeeding prepupae in the outer sapwood or thick bark of large trees. In a series of studies, we evaluated effects of grinding, chipping, and heat treatment on survival of *A. planipennis* prepupae in ash material. Heavily infested ash bolts containing roughly 8,700 prepupae were processed by a horizontal grinder with either a 2.5- or 10-cm screen. There was no evidence of *A. planipennis* survival in chips processed with the 2.5-cm screen, but eight viable prepupae were recovered from chips processed with the 10-cm screen. We chiseled additional sentinel chips with prepupae from ash logs and buried 45 in each chip pile. In total, six prepupae in sentinel chips survived the winter, but we found no sign of adult *A. planipennis* emergence from the processed chips. Subsequently, we assessed prepupal survival in chips processed by a chipper or a horizontal grinder fit with 5-, 10-, or 12.7-cm screens. An estimated 1,565 *A. planipennis* prepupae were processed by each treatment. Chips from the chipper were shorter than chips from the grinder regardless of the screen size used. No live prepupae were found in chips produced by the chipper, but 21 viable prepupae were found in chips from the grinder. Infested wood and bark chips chiseled from logs were held in ovens at 25, 40, or 60°C for 8, 24, or 48 h. Prepupal survival was consistently higher in wood chips than bark chips at 40°C, whereas no prepupae survived exposure to 60°C for eight or more hours. In a second study, prepupae in wood chips were exposed to 40, 45, 50, 55, or 60°C for 20 or 120 min. Some prepupae survived 20 min of exposure to all temperatures. No prepupae survived exposure to 60°C for 120 min, but 17% survived exposure to 55°C for 120 min, suggesting that some fraction of the population may survive internationally recognized phytosanitary standards (ISPM-15) for treatment of wood packing material.

KEY WORDS *Agrilus planipennis*, *Fraxinus*, phytosanitary treatment, invasive species

Established populations of the emerald ash borer, *Agrilus planipennis* Fairmaire (Coleoptera: Buprestidae), a phloem-feeding insect native to Asia, were discovered in 2002 in southeastern Michigan and Essex County, Ontario. Larvae, which reach 26–32 mm in length, typically feed in the phloem of ash (*Fraxinus* sp.) trees from late summer through early fall, completing four instars (Cappaert et al. 2005). Most larvae overwinter as prepupae in individual cells excavated in the thick, outer bark of large trees or ≈1 cm in depth in the outer sapwood on smaller trees with thin bark. Pupation occurs in spring, and adults emerge from May through August (Cappaert et al. 2005). Larval feeding disrupts translocation of water and nutrients, effectively girdling branches and trunks. An estimated 12–15 million ash trees, ranging from 2.5 to 200 cm in diameter and growing in urban, rural, and forested areas, have been killed by *A. planipennis* in southeastern Michigan.

Federal quarantines prohibit transport of ash trees, logs, or unprocessed wood out of southeastern Michigan, where the original *A. planipennis* infestation was centered (USDA–APHIS–PPQ 2003; MDA 2006a; Siegert et al. 2007a), and other quarantined counties. Numerous localized outlier populations have been identified in other areas of Michigan, and in Ohio, Indiana, Illinois, and Maryland (IN DNR 2006, MDA 2006b, OSU 2006; www.emeraldashborer.info). Nearly all of these outlier populations were initiated when ash nursery trees, logs, or firewood were unknowingly transported from infested areas before regulations were imposed. Although phloem in cut logs eventually becomes too dry to support *A. planipennis* development, at least some beetles can emerge from

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ash material that died or was cut during the preceding 12 mo (Petrice and Haack 2006). Major programs have been launched by federal and state regulatory agencies to contain the *A. planipennis* infestation and to prevent this invasive pest from spreading across North America.

Economic benefits might be realized by property owners if chips from infested ash trees could be safely transported and sold for use as landscape mulch, pulp, composite lumber, or electricity cogeneration. Mechanical destruction of infested trees with grinders or chippers has previously been used as a regulatory treatment for wood infested by wood-boring or phloem-feeding insects (Wang et al. 2000; Sweeney et al., unpublished data). However, effectiveness of grinding or chipping infested ash material has not been evaluated previously for *A. planipennis*, particularly in winter and early spring when most of the insects are prepupae. During this stage, the prepupae are folded into oval cells within the sapwood or thick bark, where they may be somewhat protected from desiccation or injury during processing. Moreover, prepupae require no additional feeding and uninjured individuals could potentially complete development without intact host material. In contrast, larvae that are still feeding in ash phloem between the outer bark and sapwood are more vulnerable to exposure, injury, and desiccation resulting from bark separation during grinding or chipping. We conducted a series of studies to assess 1) effects of grinding and chipping on *A. planipennis* survival, 2) overwintering survival of *A. planipennis* prepupae in chips, and 3) survival of *A. planipennis* in chips subjected to different regimes of heat treatment. These studies focused on the high-risk prepupal stage, when *A. planipennis* is least vulnerable to desiccation or injury associated with chipping or grinding and most likely to complete development in processed material.

Materials and Methods

Experiment 1: Survival of *A. planipennis* After Grinding with 2.5- and 10-cm Screens; 2002–2003 Field Study. Eight infested green ash, *Fraxinus pennsylvanica* Marsh., trees ranging from 20 to 45 cm in diameter at breast height (dbh) were felled at three sites in Wayne County on 22 October 2002. External symptoms, including >50% canopy dieback, bark cracks, and D-shaped exit holes left by emerging adults, indicated that the trees were heavily infested by *A. planipennis.* Five trees were collected from Rotary Park and one tree from Bicentennial Park in Livonia, MI, and two trees were collected from a residential development in Northville, MI.

To estimate *A. planipennis* density in each tree, we cut 30-cm-long sections from the trunk at the base and 2 m aboveground, and from two large branches (>8 cm in diameter) at 5 and 8 m aboveground. Bark was removed from one half of each trunk or branch section. Length and width of each sample area were measured, and the number of *A. planipennis* within the area was recorded. Counts were averaged to estimate density of *A. planipennis* per m^2 of phloem for each tree. Although *A. planipennis* can overwinter as early instars, this typically occurs only in healthy trees with very low *A. planipennis* densities (Cappaert et al. 2005, Siegert et al. 2007b). As density increases and trees decline, all or nearly all *A. planipennis* overwinter as prepupae. We encountered only prepupae in the areas that we sampled on these trees.

The remaining branches (>7.5 cm in diameter) and trunk pieces from each tree were cut into 2-m-long sections and labeled. Length and diameter of the sections, which approximated a cylinder, were measured and used to calculate area. To estimate the total number of *A. planipennis* in each tree, we multiplied the sum of the area of all sections from the trunk and major branches by the average density of *A. planipennis* per m^2.

The ash material was transported to an ash disposal site in Plymouth, MI, and sorted into 16 piles, each consisting of either the trunk sections or branches from one tree. One half of each of the 16 piles of wood was loaded into a model 3680 "Beast" horizontal grinder (Bandit Industries Inc., Remus, MI) fitted with a screen with 2.5- by 2.5-cm hexagonal openings. Chips from each load were collected as they emerged from the grinder, using the bucket on a front end loader. A subsample of chips was gathered into a large plastic box (60 by 45 by 45 cm) and sorted intensively to locate any pieces large enough to contain *A. planipennis* prepupae or late instars (e.g., ≥2 cm in all dimensions). Large pieces were measured and examined for the presence of *A. planipennis.* The remaining chips from each load were deposited into a single pile on the ground by the front end loader. The process was repeated until half of all trunk and branch sections had been chipped. The 2.5-cm screen on the grinder was then replaced by a screen with 10 cm hexagonal openings. As before, branches or trunk sections from each tree were processed by the grinder, and subsamples were collected for intensive examination. Remaining chips that passed through the 10- by 10-cm screen were consolidated into a second chip pile.

After examining the 16 subsamples of chips, we sorted through the two large piles. Any pieces large enough to contain intact *A. planipennis* prepupae (>2 cm in all dimensions) were counted, measured, and examined for the presence of intact *A. planipennis.* These pieces, along with the subsamples of chips, were then returned to the consolidated pile of chips produced with either the 2.5- or 10-cm screen. The two consolidated piles of chips were transported separately to an outdoor yard where they remained through the winter. Pile dimensions measured 3.8 m^3 for the chips from the 2.5-cm screen and 2.9 m^3 for the chips from the 10-cm screen, based on a conical approximation

On 29 October, temperature probes (HOBO-Pro Series Temp Ext (C), Onset Computer Corporation, Bourne, MA) were imbedded in each chip pile. Probes were placed on top of each pile to record surface temperature and were inserted at 30 and 55 cm below the surface of each pile. Temperatures were recorded

at 30-min intervals from 29 October 2002 through 19 May 2003.

On 4 May 2003, a few weeks before adult *A. planipennis* emergence was expected, we enclosed each chip pile with a fine-mesh metal screen cage (2.4 by 2.4 by 1.2 m). We suspended 10 yellow sticky cards, 25 by 40 cm (Horiver, Koppert Biological Systems, Romulus, MI), from wire supports across the top of the interior of each cage to collect any adult *A. planipennis* that emerged from chips. Sticky cards were inspected and replaced biweekly through mid-July.

To ensure that environmental conditions were suitable for *A. planipennis* development at the location where the chips were stored, six bolts (10–26 cm in diameter and 0.5 m in length) were cut from infested branches on three of the trees. These sections were placed on the ground next to the chip piles on 23 October 2002 and then left undisturbed through the winter. Sections were collected on 12 May 2003, debarked, and numbers of live and dead *A. planipennis* were recorded.

Experiment 2: Overwintering Survival of *A. planipennis* in Chips; 2002–2003 Field Study. To evaluate survival of *A. planipennis* during the winter, we prepared 45 "sentinel chips" by chiseling small sections of wood (≈5 by 8 by 1 cm) from additional infested green ash logs cut on 23 October 2002. Each sentinel chip contained a live, overwintering prepupa, identified by the characteristic frass-filled gallery terminating in a crescent-shaped opening into the sapwood. Our sentinel chips were generally similar to or smaller than the largest chips retrieved from the chip pile produced with the 2.5-cm screen (12.0 by 2.5 by 1 cm) and the chip pile produced with the 10-cm screen (15 by 6 by 1 cm). Sentinel chips ranged from 3 to 14 cm in length and from 2 to 5 cm in width, with an average size of 6.4 ± 2.1 cm (length) and 2.1 ± 1.0 cm (width). All sentinel chips were 1–2 cm in thickness. We tied a long section of nylon twine to each chip. On 23 October 2002, we buried 22 sentinel chips to a depth of 15–40 cm within the pile of chips processed through the 2.5-cm screen and 23 sentinel chips at similar depths in the pile of chips processed with the 10-cm screen. The nylon twine extended to the surface of the chip piles, allowing for retrieval of the sentinel chips on 29 April 2003. Sentinel chips were dissected on 12 May 2003 to evaluate *A. planipennis* survival. Healthy prepupae were gently removed, transferred to individual cups lined with paper toweling and held at 22 ± 2°C and 65% RH to assess survival to pupation.

Experiment 3: Chip Size and Survival of *A. planipennis* in Ash Processed by Chipping and Grinding; 2005 Field Study. We evaluated the size distribution of chips and *A. planipennis* survival in ash material processed by a Morbark model 12 Tornado wood chipper or by a model 3680 "Beast" grinder (Bandit Industries Inc., Remus, MI) fitted with screens with 5-, 10-, or 12.7-cm hexagonal openings. On 8 February 2005, we collected roughly 12 m^3 of heavily infested logs from five trees of *F. pennsylvanica* (18–25 cm dbh). Density of *A. planipennis* in adjacent trees (used in a related study) ranged from 70 to 140 larvae per m^2. An additional 5.5 m^3 of heavily infested white ash, *Fraxinus americana* L., logs (>80 *A. planipennis* per m^2) were collected at an ash disposal yard. The ash material was cut into 250 sections, each 1–2 m in length, then transported to an ash disposal yard in Plymouth, MI, on 10 February 2005. The 250 sections of ash were sorted by diameter then randomly assigned to one of five piles, ensuring that each pile of 50 logs had a similar number of relatively small and large pieces.

Ash sections from one pile, designated as control logs, were labeled and measured to estimate phloem area, ash volume, and *A. planipennis* density. Two thirds of the control logs (33 pieces) were placed into rearing barrels and held at room temperature (20 ± 2°C) for 7 wk. Adult *A. planipennis* were collected and tallied as they emerged. Density of *A. planipennis* was further assessed by measuring length and average diameter of the remaining one-third of the control logs (17 pieces), then removing a bark window (roughly 61.6 by 16.0 cm) from each log with a chisel. Larvae and prepupae of *A. planipennis* within each bark window were tallied and standardized per square meter of phloem area.

The four remaining piles of ash logs were processed as separate loads, either in the chipper (one load) or in the grinder with one of three screens. Each load of chips that emerged from the chipper or the grinder was collected in the bucket of a front end loader, then emptied into a sieve (120 by 120 by 8 cm in depth) constructed from welded-wire with 2.5- by 2.5-cm openings supported by 2.5- by 10-cm lumber sides. Chips were shaken vigorously and those that passed through the sieve were collected in tubs (68 liters) as the <2.5-cm fraction. Volume of these small chips was determined by counting the number of filled and partially filled tubs. Two subsamples (68 liters per subsample) were collected and weighed to estimate total weight of the <2.5-cm fraction of chips.

Chips retained by the 2.5 cm sieve were transferred to another sieve with 5- by 5-cm wire mesh openings and again shaken vigorously. Material that passed through this sieve was collected as the 2.5–5.0-cm fraction, and volume and weight were determined as described above. Material retained by the 5- by 5-cm sieve was transferred to a third sieve with 10- by 10-cm openings and shaken vigorously. Material that passed through this sieve was collected as the 5.0–10.0-cm fraction, and volume and weight were again determined.

Only a few large pieces of ash were retained by the 10-cm screen (>10 cm fraction), and these were examined individually. Chips that had evidence of *A. planipennis* (galleries or adherent bark) were counted, measured, and dissected on 11 February 2005, and the number of surviving *A. planipennis* was tallied.

Subsamples of 100 chips were randomly selected from the <2.5-, 2.5–5.0-, and 5.0–10.0-cm chip fractions for material processed by the chipper or the grinder with each of the three screens (total of 12 subsamples). Each chip was measured, and effects of treatment and sieve size on chip size dimensions

were evaluated with two-way analysis of variance (ANOVA) (SAS Institute 2003). When ANOVA results were significant, the Ryan–Einot–Gabriel–Welsch multiple comparison procedure was used to determine differences among treatments and among sieve sizes (Day and Quinn 1989). An α level of 0.05 was used in all tests.

Postprocessing survival of *A. planipennis* was evaluated by caging two 68-liter containers with chips from each process (four treatments) and chip size class (<2.5, 2.5–5.0, 5.0–10.0, and >10.0 cm) in the laboratory at room temperature (20 ± 2°C). Chip containers were checked periodically to assess adult beetle emergence, but no beetles emerged from any of the material. After 7 wk, the chips in each container were sorted by hand to ensure that no *A. planipennis* had emerged in the containers.

Experiment 4: Effects of Heat Treatment and Time on Survival of *A. planipennis*; 2004 Laboratory Study. To evaluate the effects of temperature on *A. planipennis* survival, we chiseled 56 bark sentinel chips and 56 wood sentinel chips from infested trees of *F. americana* on 1–7 April 2004. Each chip contained a prepupa, evidenced from the termination of a gallery and the characteristic crescent-shaped entrance to the overwintering chamber. Bark sentinel chips consisted of a piece of thick bark, chiseled from a large log (>60 cm in diameter), which contained a live *A. planipennis* prepupa in its characteristic cell. Similarly, wood sentinel chips collected from smaller logs (20–50 cm in diameter) each contained a live *A. planipennis* prepupa in a cell excavated in the outer sapwood. On average, bark sentinel chips measured 8.3 by 3.3 by 2.0 cm, whereas wood sentinel chips measured 6.5 by 3.1 by 1.3 cm.

We filled 28 plastic boxes (30 by 22 by 12 cm) with clean, ash bedding chips collected from a grinder fit with a 5-cm screen. Bedding chips were inspected to ensure that none were infested. On 7 April 2004, we buried four bark or four wood sentinel chips in the middle of each box. Boxes were held in growth chambers at 25 ± 1°C for 3 d to allow the *A. planipennis* prepupae to acclimate.

On 10 April, we randomly assigned two boxes with bark sentinel chips and two boxes with wood sentinel chips to one of seven heat × time treatments: 1) constant 25°C, 2) 8 h at 40°C, 3) 24 h at 40°C, 4) 48 h at 40°C, 5) 8 h at 60°C, 6) 24 h at 60°C, and 7) 48 h at 60°C (total of eight bark and eight wood chips per treatment). After exposure to heat treatments (±1°C) in different growth chambers, chip boxes were returned to the 25 ± 1°C growth chamber, where they remained until 15 June 2004. We checked the boxes daily beginning on 1 May 2004. Any bedding chips with mold or discoloration were removed and replaced. Vacant cells abandoned by the *A. planipennis* prepupae were noted. Adult *A. planipennis* were retrieved from each box and emergence date recorded. On 15 June 2004, all sentinel chips were retrieved and dissected to verify that unvacated cells contained dead prepupae. The proportion of chips that were vacated or contained live or dead *A. planipennis* were compared among treatments by chi-square test (PROC FREQ, SAS Institute 2003).

Experiment 5: Effects of Heat Treatment and Time on Survival of *A. planipennis*; 2005 Laboratory Experiment. On 2 February 2005, we chiseled 160 sentinel chips out of the sapwood of bolts collected from a moderately infested *F. americana* (25-cm dbh, 20–50 *A. planipennis* per m^2) cut on 1 February 2005. Chips, placed in a single layer in a plastic box, were held at 25 ± 1.0°C and 65% RH for 2 d.

On 4 February, 12 chips were randomly assigned to each of 11 heat × time treatments. Treatments included 1) constant exposure to 25°C for 4 d; (2–6) exposure to 40, 45, 50, 55, or 60°C for 20 min; or (7–11) exposure to 40, 45, 50, 55, or 60°C for 120 min. Chips for each heat × time treatment were spread out in a single layer on large manila envelopes, then set on racks in ovens (Stabil-Therm Laboratory Oven, Blue M. Electric Co., Blue Island, IL; Iso Temp Oven, Fisher International, Inc., Hampton, NH) that had been preheated to the appropriate temperature (±1°C). Chips were returned to growth chambers at 25 ± 1°C and 35% RH within 20 min after their removal from the ovens.

On 8–9 February, chips were examined carefully. If the prepupa had been slightly exposed in the chiseling process, the chip was discarded to avoid confounding physical injury with effects of the heat treatment. Remaining chips were carefully dissected and prepupae or cadavers were gently removed and left on the envelope. Prepupae were determined to be alive if they responded to gentle pressure or if they had changed position after 24 h. Prepupae were recorded as dead if they were obviously desiccated and discolored or if they seemed flaccid and were incapable of movement over a 24-h period. Prepupae that initiated pupation also were recorded. The proportion of chips that contained live or dead *A. planipennis* prepupae or pupae were compared among treatments using a chi-square test (PROC FREQ, SAS Institute 2003).

Results

Experiment 1: Survival of *A. planipennis* After Grinding with 2.5- and 10-cm Screens; 2002–2003 Field Study. Overall, *A. planipennis* density averaged 70 ± 31 and 96 ± 26 prepupae per m^2 for trunk and branch sections, respectively, in the eight *F. pennsylvanica* used for this study. Total surface area of the eight trees, estimated by a cylindrical approximation of all pieces >7.5 cm in diameter, was ≈105 and 8.8 m^2 for trunk and branch sections, respectively. After subtracting the area of pieces that we destructively sampled, we estimated that there were roughly 868 *A. planipennis* in the branch pieces and 7,834 *A. planipennis* in the trunk pieces from the eight trees.

Each subsample that we collected from branch and trunk sections of each tree that passed through the 2.5- and 10-cm screens on the grinder consisted of ≈0.12 m^3 of chips. Subsamples were intensively sifted by hand and examined to determine whether large

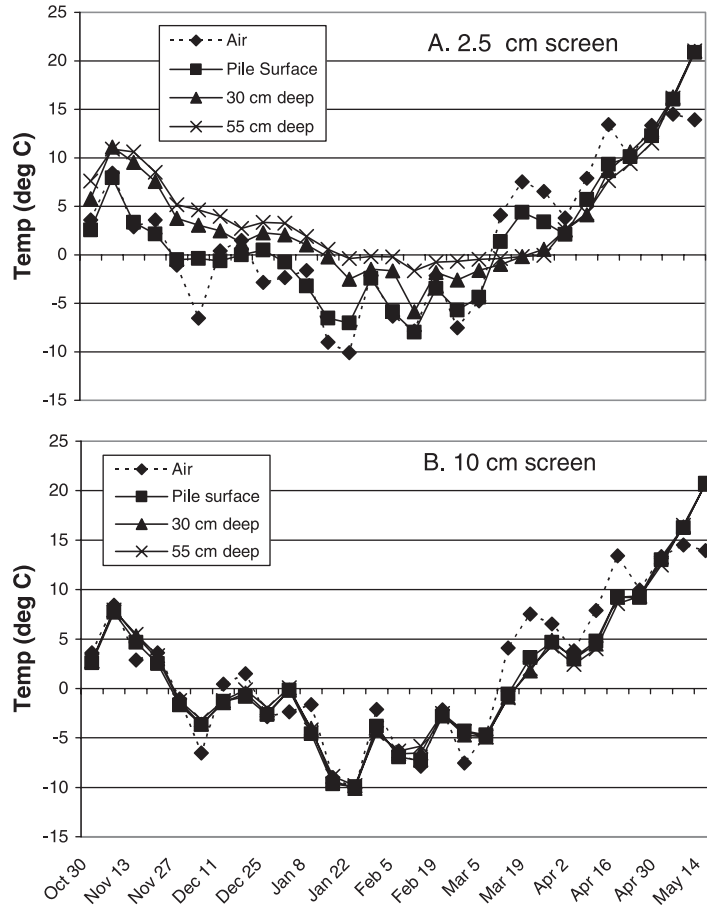

Fig. 1. Mean weekly temperatures recorded on the surface and at 30 and 55 cm in depth in piles of green ash chips processed by a grinder with either a 2.5- (A) or a 10-cm screen (B) compared with air temperature from 30 October 2002 to 14 May 2003 in Wayne County, MI.

chips with *A. planipennis* were present and whether large chips (≥2 cm in all dimensions) capable of supporting *A. planipennis* emerged from the grinder. We found no *A. planipennis* life stages in any of the subsamples.

We also sorted through the two consolidated piles of chips. In the pile of chips processed with the 10-cm screen, we found eight chips that contained *A. planipennis* prepupae, all of which seemed to be alive and viable. Several other pieces of ash in this pile were <10 cm in two directions, but they exceeded 10 cm in one direction. The two largest chips in the chip pile produced with the 10-cm screen measured 14 by four by 2.5 cm and 15 by 6 by 1 cm. In contrast, most material that passed through the 2.5-cm screen was ground to a fine, chaff-like consistency. The two largest chips produced with the 2.5-cm screen measured 12 by 1 by 0.75 cm and 12 by 2.5 by 1 cm. We did not find any infested chips nor any chips that seemed large enough to sustain a larva in the material processed with the 2.5-cm screen.

Adult *A. planipennis* are phototropic, and we have repeatedly observed beetles fly toward light. No *A. planipennis* adults, however, were captured on the sticky cards suspended inside the cages above the piles of chips produced with either the 10-cm screen or the 2.5 cm screen. Similarly, we did not find any live or dead adults inside the cages, despite periodic inspection of the chip piles from late May through July.

Experiment 2: Overwintering Survival of *A. planipennis* in Chips; 2002–2003 Field Study. Mean weekly temperatures within the pile of *F. pennsylvanica* chips produced with the 2.5-cm screen differed somewhat from temperatures within the chip pile produced with the 10-cm screen (Fig. 1). For the chip pile produced with the 2.5-cm screen, temperatures at 30 and 55 cm in depth within the pile were warmer and less variable than air temperatures during the weeks from 30 October 2002 to 19 March 2003. From 19 March to 30 April, air temperatures were higher and fluctuated more than temperatures at 30 and 55 cm in depth within the pile, which increased more slowly and steadily. By 14 May, temperatures at the 30- and 55-cm depths within the pile exceeded air temperatures. Temperatures at the surface of the pile were generally intermediate between air temperatures and

Table 1. Maximum, minimum, and mean ± SE air temperatures and temperatures on the surface and at 30- and 55-cm depths measured from 29 October 2002 to 19 May 2003[a] within piles of ash chips[b] produced by a grinder with a 2.5- or 10-cm screen in Wayne County, MI

	Temp (°C)			
	Air[c]	Surface of pile	30-cm depth	55-cm depth
Chip pile from 2.5-cm grinder screen				
Max. (14 May 2003)	21.1	37.3	36.6	35.3
Min. (3 Mar. 2003)	−22.8	−17.7	−2.9	−0.6
Mean	1.74 ± 0.56	1.71 ± 0.08	3.59 ± 0.06	4.40 ± 0.06
Chip pile from 10-cm grinder screen				
Max. (14 May 2003)	21.1	37.5	34.0	36.1
Min. (3 Mar. 2003)	−22.8	−5.3	−6.3	−3.8
Mean	1.74 ± 0.56	1.14 ± 0.08	1.20 ± 0.08	1.25 ± 0.08

Air and chip pile temperatures are presented for the hottest and coldest dates within the recording period.
[a] Temperatures in the green ash chip piles were recorded at 30-min intervals by a HOBO-Pro Series Temp Ext (C) Onset recorder.
[b] Chips were from infested green ash trees.
[c] Air temperatures were obtained from the National Oceanic and Atmospheric Administration (NOAA 2002, 2003).

within pile temperatures. In the pile of chips produced with the 10-cm screen, temperatures at the pile surface and at 30 and 55 cm in depth within the pile were similar and tracked air temperatures closely (Fig. 1).

The maximum air temperature recorded during the period from 30 October 2002 until 18 May 2003 was 21.1°C on 14 May 2003. On that day, surface temperatures of both chip piles exceeded 37°C (Table 1), whereas temperatures within the chip piles ranged between 34.0 and 36.1°C. The minimum air temperature recorded was −22.8°C on 3 March 2003. Temperatures at the surface and within the chip piles were warmer than the air temperature that day and ranged from −0.6°C at the 55-cm depth in the chip pile produced with the 2.5-cm screen to −17.7°C at the surface of that pile (Table 1). The overall mean air temperature during the entire recording period was 1.74°C. The highest overall mean temperature recorded within the chip piles was 4.4°C at the 55-cm depth within the chip pile produced with the 2.5-cm screen and the lowest overall mean temperature within the chip piles was 1.20°C at the 30-cm depth within the chip pile produced with the 10-cm screen (Table 1).

The *F. pennsylvanica* sentinel chips from both chip piles were retrieved and dissected in May 2003, a few weeks before adult emergence was expected, to determine whether *A. planipennis* prepupae had survived the winter. In the pile of chips processed with the 2.5-cm screen, 16 of the original 22 prepupae had vacated their chip. We did not recover the prepupae, but they undoubtedly died from exposure and desiccation. We recovered three live prepupae; one prepupa survived to the pupal stage, whereas two prepupa were injured during the dissection, but likely would have developed successfully. We also removed three cadavers from their respective chips. In the chip pile produced with the 10-cm screen, 18 of the 23 prepupae had vacated the chip. We recovered two cadavers and three live prepupae from the chips. One live prepupa was injured during dissection, but the other two prepupa survived and successfully pupated. Overall, 13.3% of the prepupae in the sentinel chips overwintered successfully.

In comparison, when we dissected the six ash bolts that were stacked next to the chip piles throughout the winter, we found that 91% of the *A. planipennis* were alive, indicating that the ash material and environmental conditions at the site were suitable for survival. We recovered 35 *A. planipennis* in total, including 25 live prepupae (71.4%), three dead prepupae (8.6%), and seven live pupae (20.0%). Mean density of *A. planipennis* in the six branch sections was estimated to be roughly 111 prepupae per m^2, comparable with estimates we derived for branches from all eight trees.

Experiment 3: Chip Size and Survival of *A. planipennis* in Ash Processed by Chipping and Grinding; 2005 Field Study

Assuming cylindrical dimensions for each piece, the total surface area of the control logs (used to estimate *A. planipennis* density) was 11.94 m^2 and ash volume was 0.387 m^3. In total, 931 *A. planipennis* adults emerged from the 33 logs held in the laboratory and potential emergence of *A. planipennis* from all 50 logs in each pile was estimated to be 1,397 beetles. The mean density of *A. planipennis* in the control logs that we sampled with bark windows was 146 ± 21 per m^2, including 14 ± 5 feeding larvae and 131 ± 19 prepupae per m^2. Based on the calculated surface area of the logs in the control pile, we estimated that 1,565 *A. planipennis* were present in each pile of ash logs before processing. This estimate corresponded closely to our estimate of potential adult emergence, which would be expected to be somewhat lower given that some prepupae would likely fail to complete development.

The chipper consistently produced smaller chips than the grinder, regardless of the size of the screen used in the grinder. Overall, 84% by mass (kilograms) of the chips processed by the chipper were included in the smallest size class (<2.5-cm fraction) compared with 39–55% of the chips processed by the grinder (Table 2). Similarly, only 3% of the chips that emerged from the chipper were retained in the 5.0–10.0-cm chip fraction compared with 15–27% of the material processed by the grinder.

Table 2. Distribution by mass (M, in kilograms) and volume (Vol, in liters) of ash chips[a] retained by 2.5-, 5-, and 10-cm mesh sieves after processing by a chipper or a grinder fit with screens with 5-, 10-, or 12.7-cm hexagonal openings

Treatment	2.5-cm sieve		5-cm sieve		10-cm sieve		Total	
	M (% total wt)	Vol	M (% total wt)	Vol	M (% total wt)	Vol	M	Vol
Chipper	287 (84)	1,021	44 (13)	204	12 (3)	79	343	1,305
Grinder; 5-cm screen	118 (55)	750	63 (30)	470	33 (15)	251	215	1,472
Grinder; 10-cm screen	87 (39)	545	75 (34)	564	60 (27)	491	223	1,601
Grinder; 12.7-cm screen	84 (40)	573	79 (37)	566	50 (23)	409	213	1,548

[a] Chips were from infested green ash and white ash trees.

In material processed by the grinder, chips were consistently smaller than the size of the screens in two dimensions, but not necessarily in the third dimension. Mean length of chips, for example, ranged from 6.50 to 17.1 cm for material processed in the grinder with 5-, 10-, or 12.7-cm openings (Table 3). We compared the size of chips retained by each sieve and found that for each chip fraction, chips processed by the chipper were similar to or smaller in length than chips produced by the grinder with any of the three screens (Table 3). Width and depth of chips produced by the chipper were generally similar to or slightly greater than chips produced by the grinder. Differences in chip dimensions between the chipper and grinder were most pronounced for the smallest chips (<2.5-cm fraction); length of these chips was significantly shorter when material was processed by the chipper compared with the grinder (Table 3). The maximum dimensions (length by width by depth) of the 15 largest chips in the 5.0–10.0-cm fraction for the chipper averaged 37 by 9 by 5 cm compared with dimensions of 50 by 7.5 by 6 cm, 56 by 10 by 7.5 cm, and 64 by eight by 6.4 cm for the grinder fit with 5-, 10-, and 12.7-cm screens, respectively.

Table 3. Mean ± SE dimensions for 100 chip subsamples collected after ash material[a] was processed by a chipper or grinder fit with screens with 5-, 10-, or 12.7-cm hexagonal openings

Treatment/sieve mesh (cm)	Length (cm)	Width (cm)	Depth (cm)
Chipper			
2.5	3.3 ± 0.2cB[b]	1.10 ± 0.40cA	0.40 ± 0.02cA
5.0	8.8 ± 0.4bB	1.30 ± 0.10bA	0.60 ± 0.10bA
10.0	15.2 ± 0.5aAB	1.50 ± 0.10aA	0.80 ± 0.04aA
Grinder; 5-cm screen			
2.5	6.5 ± 0.4cA	0.51 ± 0.03bB	0.29 ± 0.01bB
5.0	10.5 ± 0.3bA	1.17 ± 0.06aA	0.75 ± 0.04aA
10.0	17.1 ± 0.7aA	1.20 ± 0.10aB	0.70 ± 0.01aAB
Grinder; 10-cm screen			
2.5	7.6 ± 0.5bA	0.74 ± 0.10aB	0.36 ± 0.02bA
5.0	8.6 ± 0.6bB	0.85 ± 0.05aB	0.47 ± 0.04aB
10.0	14.0 ± 0.6aB	0.90 ± 0.09aB	0.52 ± 0.03aC
Grinder; 12.7-cm screen			
2.5	6.7 ± 0.4cA	0.68 ± 0.08bB	0.36 ± 0.02cA
5.0	8.9 ± 0.3bB	0.85 ± 0.05bB	0.49 ± 0.04bB
10.0	17.1 ± 0.6aA	1.10 ± 0.10aB	0.60 ± 0.04aBC

Chips from each chipping or grinding treatment were sorted using sieves with 2.5-, 5.0-, or 10.0-cm mesh and subsamples were collected from the material retained by each sieve.

[a] Chips were from infested green ash and white ash trees.

[b] Differences in mean dimensions among sieve sizes within a treatment in a column are indicated by different lower case letters. Differences in mean dimensions among treatments for a given sieve size within a column are indicated by different upper case letters. ($P < 0.05$; Ryan–Einot–Gabriel–Welsch multiple comparison test).

We examined, measured dimensions, and dissected the large chips retained by the 10-cm sieve (>10-cm fraction) after each processing treatment. We found no viable *A. planipennis* prepupae in the eight large chips that emerged from the chipper (Table 4). In total, 52 large chips that emerged from the grinder had intact bark and/or *A. planipennis* galleries that indicated they could be infested. In all, 22 of the chips from the grinder were infested, and we found a total of 30 *A. planipennis* (Table 4). Nine of the prepupae were obviously injured by the grinding process and would have died, but 21 appeared viable (Table 4).

In total, 32 containers (each 68 liters) of chips from the <2.5-, 2.5–5.0-, 5.0–10.0-, and >10.0-cm size classes produced by each of the four treatments were held in the laboratory for 7 wk to allow any A. *planipennis* within the chips to complete development and emerge. The containers were checked periodically and sorted intensively at the end of 7 wk. No *A. planipennis* beetles emerged from any container, and none of the chips appeared to be infested.

As we collected processed ash material, we occasionally observed unusually large pieces emerging from the grinder, regardless of screen size. These anomalous pieces were larger in every dimension than the screen openings and could not have passed through the screen. Further investigation revealed the presence of a 15–20-cm-wide gap above the top of the grinder screen, which allowed pieces of ash material to emerge from the grinder without passing through the screen. This gap occurred when the interior guides for the screen were modified by the operator, which caused the screen to drop too low. The modification was recent and the grinder operator was unaware of the problem until we called it to his attention. Some of these large pieces, which we collected and dissected, contained live *A. planipennis* prepupae, which presumably could have emerged.

Experiment 4: Effects of Heat Treatment and Time on Survival of *A. planipennis*; 2004 Laboratory Study. In total, 75% of the *A. planipennis* prepupae in the *F. americana* chips survived exposure to a constant 25°C for 48 h (Table 5). Overall, survival in bark chips was significantly lower than survival in sapwood chips ($t = 4.54$, $P = 0.0005$) (Table 5). In the bark chips held at 40°C, 37.5–50% of the *A. planipennis* survived exposure

Table 4. Number and mean ± SE dimensions of ash chips[a] with *A. planipennis* prepupae retained by a sieve with 10-cm openings after ash material was processed by a chipper or a grinder fit with screens with 5-, 10-, or 12.7-cm hexagonal openings

	Chipper	Grinder, 5-cm screen	Grinder, 10-cm screen	Grinder, 12.7-cm screen
No. large chips examined	8	12	17	21
Chip length (cm)	25.6 ± 2.02	32.4 ± 3.28	30.9 ± 2.98	29.1 ± 3.83
Chip width (cm)	4.6 ± 0.73	5.6 ± 0.31	5.9 ± 0.57	4.6 ± 0.37
Chip depth (cm)	2.5 ± 0.51	4.1 ± 0.38	4.3 ± 0.51	3.29 ± 0.24
No. chips with prepupae	0	4	9	9
Total no. of prepupae	0	4	14	12
No. of intact prepupae	0	3	9	9

[a] Chips were from infested white ash trees.

for 8–48 h, whereas in the wood chips, at least 75% of the *A. planipennis* survived exposure. Prepupae also were much more likely to abandon bark chips than wood chips as exposure to heat accumulated. In total, 23% of the prepupae vacated the bark chips compared with only 5% of the prepupae in the wood chips (Table 5). No *A. planipennis* in any of the bark or wood chips survived exposure to 60°C regardless of whether exposure lasted for 8, 24, or 48 h.

Experiment 5: Effects of Heat Treatment and Time on Survival of *A. planipennis*; 2005 Laboratory Study

In the control treatment, where *F. americana* chips were exposed to a constant 25°C for 120 min, 75% of *A. planipennis* prepupae survived, and 25% had pupated when chips were dissected. At least some prepupae survived 20 min of exposure to all temperatures ranging from 40 to 60°C (Table 6). Prepupae survival in chips exposed to heat for 20 min ranged from 30 to 64%, and 20–40% of the prepupae pupated.

In chips exposed to heat for 120 min, survival of *A. planipennis* declined as temperature increased (Table 6). At 55°C, only 17% of the prepupae survived, and no prepupae survived exposure to 60°C for 120 min. The pupation rate in chips exposed for 120 min also declined with increasing temperature. At temperatures of 40, 45, and 50°C, pupation rates were 27, 43, and 9%, respectively, whereas no pupation occurred in chips exposed to 55 or 60°C. Percentage survival of *A. planipennis* in chips held at 60°C for 120 min was significantly lower than survival in control chips held at constant 25°C. Percentage of pupation of *A. planipennis* in chips held at 55 or 60°C for 120 min was significantly lower than pupation in control chips held at constant 25°C (Table 6).

Table 5. Percentage of ash bark and wood chips[a] found to be vacant or containing dead or surviving *A. planipennis* prepupae after different heat treatment regimes in the 2004 laboratory study

Treatment	Chip type	% chips with *A. planipennis*		
		Vacant[b]	Dead	Alive
Control (25°C)	Bark	25.0	12.5	62.5
	Wood	0.0	12.5	87.5
8 h at 40°C	Bark	0.0	50.0	50.0
	Wood	12.5	0.0	87.5
24 h at 40°C	Bark	12.5	50	37.5
	Wood	0.0	0.0	100.0
48 h at 40°C	Bark	37.5	25.0	37.5
	Wood	0.0	25.0	75.0
8 h at 60°C	Bark*[c]	12.5	87.5	0.0
	Wood*	0.0	100.0	0.0
24 h at 60°C	Bark*	37.5	62.5	0.0
	Wood*	25.0	75.0	0.0
48 h at 60°C	Bark*	37.5	62.5	0.0
	Wood*	0.0	100.0	0.0

n = 8 bark and 8 sapwood chips per treatment.
[a] Chips were from infested white ash trees.
[b] Prepupae that vacated chips presumably died from desiccation.
[c] Percentage distributions for treatments followed by an asterisk (*) were significantly different from the percentage of distributions for the control treatment of the same chip type ($P < 0.05$; χ^2 test).

Discussion

Suitable options for disposal of ash material will become an increasingly widespread issue in municipalities with high-density *A. planipennis* populations and outlier sites targeted for containment or eradication activities. Grinding, chipping, and heat treatments have been previously used for effective phytosanitary treatment of wood infested with wood-boring insects (USDA–APHIS 2000, Sweeney et al., unpublished data), but our studies represent the first evaluation of such treatments for the phloem-feeding *A. planipennis.*

Table 6. Percentage of *A. planipennis* prepupae that survived and pupated when ash chips[a] were exposed to different heat treatment regimes for either 20 or 120 min

Min exposed	Temp (°C)	n[b]	Survival (%)	Pupation (%)
Control–constant	24	12	75.0	25.0
20	40	10	50.0	20.0
	45	11	63.6	36.4
	50	10	30.0	30.0
	55	12	50.0	25.0
	60	10	50.0	40.0
120	40	11	63.6	27.3
	45	7	71.4	42.9
	50	11	36.4	9.1
	55	12	16.7	0.0*[c]
	60	12	0.0*	0.0*

[a] Chips were from infested white ash trees.
[b] We began with 12 chips per treatment, but chips were excluded if the prepupa protruded from the chip and was exposed during treatment.
[c] Percentages in the same column followed by the symbol * were significantly different from the control ($P < 0.05$; χ^2 test).

We focused on *A. planipennis* survival in ash that was cut and processed during winter, when most larvae were in the prepupal stage and have the greatest chance of surviving chipping, grinding, or exposure to heat. After feeding is completed, prepupae fold themselves into elliptical cells excavated to ≈1 cm in depth in the outer sapwood or in the thick, outer bark on the trunks of large trees. Prepupae would be less affected by phloem desiccation or deterioration than feeding larvae and more protected from physical injury or desiccation than other life stages. If prepupae were not physically injured or exposed during processing, they would presumably be able to successfully pupate and emerge as adults. Prepupae removed from infested logs and placed individually in tissue culture plates, for example, successfully pupated and developed into feeding adults (Bauer et al. 2004).

To date, many of the infested ash trees removed at outlier sites or in municipalities with high-density *A. planipennis* populations have been processed in large, horizontal grinders comparable with the models used in our studies. Some chips from infested ash trees are used locally for products such as compost or mulch, but many loads of chips have been burned at electricity cogeneration plants. Grinders, which smash and crush large pieces of wood into smaller pieces, rely on a screen or grate to control the maximum particle size (Rynk et al. 1992). Advantages of using grinders include the ability to vary chip size and their capability for handling large pieces such as entire tree trunks. Depending on the model, 45–90 metric tons/h of material can be processed (Rynk et al. 1992). Particle size of material processed by grinders is known to vary, which can be a problem when uniform particle size is required for end-products such as chemical pulping or gasification and pyrolysis to produce oil or gas (Glenn 1997, Smith and Javid 1999, Sengupta 2002). A mix of large and small chips, however, facilitates decomposition and is preferred for compost generation (Rynk et al. 1992, Resource Management Group, Inc., 2006).

Our results showed that a high proportion of *A. planipennis* were killed during the grinding process. In 2002, for example, we found no evidence that any of the estimated 4,350 prepupae survived in material processed by a grinder fit with a 2.5-cm screen. Using the 2.5-cm screen required more time for processing than larger screens and yielded 3.8 m^3 of light, almost powdery chips that resembled chaff. Fine material may be undesirable for burning in electricity cogeneration plants because of the difficulty of forcing sufficient air through very fine particles to promote efficient combustion (Payne et al. 1984, Sengupta 2002). Chip size requirements of cogeneration plants vary, however, depending on the equipment and combustion process in use (e.g., direct firing in suspension or on grates) (FAO 1990), whereas some potential applications for wood fiber, such as pellets, actually require material to be finely ground (Badger 2002). Larger chips are generally more efficient to produce than small chips, and they may be better suited than small chips for erosion control (Buchanan et al. 2002) or in some grate combusters used by cogeneration plants (Ingham 1995).

When screens larger than 2.5 cm were used in our studies, however, at least some *A. planipennis* survived the grinding process in every trial. Most of the viable prepupae that we recovered were found in long chips that retained some intact bark. These pieces were smaller than the screen openings in two dimensions, but they exceeded the screen size in the third dimension. With a 10-cm screen, for example, we retrieved pieces that were 50–60 cm in length. In 2002, 0.18% of the prepupae recovered from 2.9-m^3 pile of chips were still alive after grinding with a 10-cm screen. In 2005, we recovered a total of 21 viable prepupae from chips processed by the grinder for an overall survival rate of 0.45%. We determined that grinding with 5-, 10-, or 12.7-cm screens resulted in prepupal survival of 0.19, 0.57, and 0.57%, respectively, in chip piles that ranged from 1.47 to 1.60 m^3 in volume. Although only a small proportion of *A. planipennis* survived grinding, the volume of chips that may be produced in infested areas can be substantial. For example, ash disposal yards in southeast Michigan processed >245,000 metric tons of urban and suburban ash trees from 2003 to 2005 (Poland and McCullough 2006).

The largest fragments of infested material were recovered in our 2005 study, when several kindling-sized pieces of ash passed over the top of the screen in the grinder. This occurred after the operator removed and modified a screen, and then returned it to the grinder. Given the substantial amount of dust and debris generated by the grinder, it was not surprising that the operator failed to notice the problems with the screen until we pointed it out. Although this is likely an anomaly, it does highlight the need for careful and frequent inspection of equipment, especially when equipment is used for regulatory treatments.

Processing infested ash material with the chipper was more effective than we had expected. Chippers differ from grinders in that they use a sharp edge to reduce large material to small particles (Glenn 1997). In some models, material is fed into a shredder, which usually consists of counter-rotating shafts fitted with fixed knives or rippers (Rynk et al. 1992) that shear and cut wood as it is drawn through the machine (Williams and Engel 1997). Most chippers, however, use a large disc or drum with embedded knives; the disk turns as the wood is held against it. In our 2005 study, we found no evidence that any of the estimated 1,565 *A. planipennis* survived in 1.3 m^3 of chips. Density of chips emerging from the chipper, for example, was 35–40% greater than the density of chips emerging from the grinder. The relatively uniform and small chips produced by the chipper would be acceptable for many heat- and cogeneration plants (Asikainen and Pulkkinen 1998). Chippers can be designed and modified to optimize chip length and thickness by adjusting parameters such as chip length setting, spout angle, knife edge angle, pull-in angle, λ angle, and knife velocity (Smith and Javid 1999). Overall, our results suggest that chippers warrant further consideration for use in regulatory situations. They produced more uniform and smaller chips that were less likely

to contain viable *A. planipennis* than the grinder fit with any screen larger than 2.5 cm.

Our estimates of *A. planipennis* survival after grinding probably represent a worst-case scenario and may overestimate the proportion of prepupae that would successfully complete development. We assumed at the beginning of our studies that if *A. planipennis* prepupae avoided physical injury during chipping or grinding, they would be likely to complete their life cycle and emerge as adults. We found, however, that >85% of the prepupae in the sentinel chips that we buried in chip piles died during the 2002–2003 winter. In addition, we returned chips that contained viable *A. planipennis* to the chip piles then enclosed the chips in spring to collect emerging adults. Despite regular inspections of the chips, cages, and suspended sticky traps, we found no evidence that *A. planipennis* adults emerged from either chip pile. Similarly, subsamples of chips processed by the chipper or grinder in 2005 were held in tubs and regularly inspected for several weeks, but no adult beetles emerged.

Mortality of *A. planipennis* that survived the initial grinding process could have been caused by chip desiccation or increased exposure of the prepupae to unsuitable temperatures, humidity, or pathogens. In some instances, prepupae simply left the chip when conditions became unsuitable. For example, 14% of the prepupae in our 2004 and 2005 heat treatment studies vacated chips during or after exposure to heat and 76% of the prepupae in the 2002–2003 sentinel chips left the chips during the winter. Prepupae that leave a chip have virtually no chance of survival because of rapid desiccation.

Increased temperatures created by microbial decomposition can be another source of *A. planipennis* mortality if large chip piles accumulate in disposal yards or processing facilities (Recycled Organics Unit 2000). Temperatures generated by decomposition depend on the material, particle size, moisture content, aeration, and height of the compost pile (Glenn 1998). Composting temperatures of ≈55°C or greater (from microbial activity) are typically required for a minimum period of 3 d to kill pathogens or weed propagules (Recycled Organics Unit 2000).

The chip piles that we generated in 2002–2003 were relatively small and heat generated by microbial decomposition was probably minimal. Heat generation is proportional to the volume of chip piles, whereas heat loss is proportional to surface area (Tsuchiya and Sumi 1977). Compost piles >3.6 m high are associated with extreme heat generation and spontaneous combustion (Glenn 1998, Rynk 2000). Temperatures within our small chip piles were not substantially warmer than ambient conditions and never reached 56°C, the temperature required for regulatory heat treatment of infested wood (FAO 2002) and pasteurization of compost (Recycled Organics Unit 2000).

Temperatures within the pile of small chips produced by the grinder with the 2.5-cm screen were warmer and fluctuated less than air temperatures throughout the winter, and the daily minimum temperature was considerably warmer than air temperature on the coldest day of winter. This may have occurred because of heat generated by microbial processes associated with composting or because of fewer air voids in the dense pile of small chips. In contrast, relatively little heat was generated by the pile of larger chips processed with the 10-cm screen. Overall mean temperatures in the pile of large chips were actually cooler than the overall mean air temperature during the recording period. Sawdust and smaller wood particles are known to self-heat more readily than large particles because of their lower thermal conductivity which accumulates heat more easily and their greater surface area, which is oxidized more readily (Tsuchiya and Sumi 1977).

If *A. planipennis* do survive grinding or chipping processes, heat treatment may be an option for deregulating chips produced from infested ash material that are targeted for specific uses such as compost or mulch. Treating infested wood with heat is a widely accepted regulatory practice in many countries. New worldwide standards recently proposed by the International Plant Protection Convention require wood packing material to be treated with heat in a schedule that achieves a minimum core temperature of 56°C for 30 min (FAO 2002) or to be fumigated with methyl bromide. This International Standard for Phytosanitary Measures, commonly known as ISPM-15, is being adopted by the United States and other countries (USDA–APHIS 2004). The Canadian Heat-Treated Wood Products Certification Program for Export, administered by the Canadian Food Inspection Agency, similarly requires that all wood products and packing material for export be heated to a core temperature of 56°C for 30 min (CFIA 2006).

Survival of *A. planipennis* in chips exposed to heat depended on the duration of exposure as well as temperature, and it varied between prepupae in bark and wood chips. No *A. planipennis* survived when chips were exposed to 60°C for ≥2 h in either of our studies, but 50% of the prepupae did survive 1 h of exposure to 60°C. At 55°C, just slightly below the regulatory standard of 56°C, 50% of prepupae survived 20 min of exposure, and 17% survived 2 h of exposure. We also found that 30–73% of *A. planipennis* prepupae survived in chips exposed to 40–50°C for up to 2 h. In comparison, late instars of the cerambycids *Tetropium fuscum* (F.) and *Tetropium cinnamopterum* (Kirby) died after wood was exposed to 50°C for 30 min or to 55°C for 15 min (Mushrow et al. 2004). Survival of *A. planipennis* was roughly twice as high for prepupae in wood chips compared with those in bark chips, which may relate to the rate of moisture loss or the insulation provided by bark versus wood. Several of the *A. planipennis* exposed to sublethal temperatures in our 2005 study began to pupate, a response consistent with behavior of overwintering *A. planipennis* brought indoors for rearing. Prepupae in logs exposed to several weeks of cold weather or storage complete development and emerge as adults within 4 wk after logs are moved to 24°C conditions (Bauer et al. 2004). Our temperature studies were conservative and again, may represent a worst-case scenario. Additional research is needed to determine whether exposure to warm but nonlethal tempera-

tures affects fecundity, life span, or other traits of *A. planipennis*.

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