Approved Quarantine Treatment for Hessian Fly (Diptera: Cecidomyiidae) in Large-Size Hay Bales and Hessian Fly and Cereal Leaf Beetle (Coleoptera: Chrysomelidae) Control by Bale Compression

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ABSTRACT A quarantine treatment using bale compression (32 kg/cm^2 pressure) and phosphine fumigation (61 g/28.3 m^3 aluminum phosphide for 7 d at 20°C) was approved to control Hessian fly, *Mayetiola destructor* (Say), in large-size, polypropylene fabric-wrapped bales exported from the western states to Japan. No Hessian fly puparia (45,366) survived to the adult stage in infested wheat, *Triticum aestivum* L., seedlings exposed to the treatment in a large-scale commercial test. Daily temperatures (mean ± SEM) inside and among bales in three test freight containers were 17.8 ± 0.2 front top, 17.0 ± 0.2 front bottom, 17.3 ± 0.2 middle bale, 15.7 ± 0.3 middle air, 18.5 ± 0.1 back top, and 18.1 ± 0.1°C back bottom, allowing the fumigation temperature to be established at ≥20°C. Mean fumigant concentrations ranged from 208 to 340 ppm during the first 3 d and ranged from 328 to 461 ppm after 7 d of fumigation. Copper plate corrosion values inside the doors, and in the middle of the large-size bales in all locations indicated moderate exposure to hydrogen phosphide (PH_3). PH_3 residues were below the U.S. Environmental Protection Agency tolerance of 0.1 ppm in animal feeds. The research was approved by Japan and U.S. regulatory agencies, and regulations were implemented on 20 May 2005. Compression in large-size bale compressors resulted in 3–3.6 and 0% survival of Hessian fly puparia and cereal leaf beetle, *Oulema melanopus* (L.), respectively. Bale compression can be used as a single treatment for cereal leaf beetle and as a component in a systems approach for quarantine control of Hessian fly.

KEY WORDS *Mayetiola destructor*, *Oulema melanopus*, pressure, hydrogen phosphide, fumigation

Hessian fly, *Mayetiola destructor* (Say), is a U.S. pest of regulatory concern in hay exported to foreign markets from the western states. The biology of Hessian fly and another regulated pest, cereal leaf beetle, *Oulema melanopus* (L.), has been discussed in relation to hay exports in previous work (Yokoyama et al. 1993a, 2002). Hay is produced from forage that is cut, dried, and baled and used for animal feed. Hay species exported to Japan and other Asia-Pacific and Middle East markets include timothy, *Phleum pretense* L.; alfalfa, *Medicago sativa* L.; oat, *Avena sativa* L.; sudangrass, *Sorghum bicolor* (L.) subsp.. *sudanensis;* Bermuda grass, *Cynodon dactylon* (L.) Pers.; and ryegrass (*Lolium* spp.). Other species of exported non-Triticeae grasses include orchardgrass, *Dactylis glomerata* L.; klinegrass, *Panicum coloratum* L.; fescue (*Festuca* spp.); bluegrass (*Poa* spp.); teff, *Eragrostis tef* (Zucc.) Trotter; bentgrass (*Agrostis* spp.); and meadow foxtail, *Alopecurus pratensis* L.

Freight containers of hay may be rejected at destination ports upon inspection, if Hessian fly hosts including wheat, *Triticum aestivum* L; barley, *Hordeum vulgare* L.; and grasses of *Agropyron* spp. are found in the bales (Storey and Hatchett 1978). Of these weed contaminants, barley (*Hordeum* spp.) was shown to be a poor host by Chen et al. (2009). Of the hay species that are exported, alfalfa is not a known host of Hessian fly, and larvae or pupae do not develop from eggs laid on timothy, oat, or a perennial ryegrass, *Lolium perenne* L. (Harris et al. 1996). Although *Lolium* spp. were reported as hosts by Jones (1939), it may have actually been an observation for *Agropyron* spp. (Zeiss et al. 1993). Zeiss et al. (1993) also found pest reproduction to be negligible on bermuda grass, an exported hay and other non-Triticeae grasses. Based on these observations for hay and weed species, the Hessian fly puparial stage (Storey and Hatchett 1978) may occur in wheat, and *Agropyron* spp. and *Elymus* spp. (Jones 1939) grass weeds.

Physical techniques to control agricultural pests have been reviewed by Vincent et al. (2003) and include thermal and mechanical methods. Heat treatments to control Hessian fly in hay exported from Canada were studied by Sokhansanj et al. (1990, 1992,

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1993), Sokhansanj and Wood (1991), and Opoku et al. (2001, 2002). Yokoyama et al. (1994a) showed that U.S. hay harvesting practices and field drying conditions caused high insect mortality. Hydraulic compression of bales to increase the amount of hay in freight containers for export was proposed as a single treatment to control Hessian fly (Yokoyama et al. 1993a) in U.S. standard bales ≈122 cm in length that were compressed to ≈46–61 cm in length, and in Canadian timothy bales (Tabil et al. 2006). Standard bale compression also was shown to control cereal leaf beetle, *Oulema melanopus* (L.) (Yokoyama and Miller 2002).

Chemical fumigation is a postharvest treatment that can provide a high level of security for exported commodities to ensure shipments are free of quarantine pests. A multiple quarantine treatment composed of two single treatments, bale compression (≥80 kg/cm^2) and hydrogen phosphide (PH_3) fumigation (60 g/28.3 m^3 aluminum phosphide for 7 d at 22°C) was developed and approved to control Hessian fly puparia (Yokoyama et al., 1993a,b, 1994a,b, 1996, 1999) and cereal leaf beetle (Yokoyama and Miller 2002) in compressed standard bales and polyethylene film-wrapped units of compressed standard bales of hay (Yokoyama et al. 1999). Carbonyl sulfide has been proposed as a fumigant for hay exported from Australia (Weller 2003).

At the turn of the century, a new quarantine treatment was under development to control Hessian fly in large-size, polypropylene fabric-wrapped bales of hay. The weight of large-size bales ranged from 408.2 to 453.6 kg; the height ranged from 76.2 to 78.7 cm; the length ranged from 109.2 to 121.9 cm; and the width ranged from 114.3 to 121.9 cm. The large size of the bales versus standard bales, the unique bale processing method using high capacity machinery, and a woven fabric covering excluded the procedure from previously developed multiple quarantine treatment for compressed standard bales. Furthermore, the effect of hydraulic compression in compressors to form large-size bales had not been tested on Hessian fly puparia or cereal leaf beetle.

A test protocol to confirm the efficacy of compression and PH_3 fumigation to control Hessian fly in the large-size, polypropylene fabric-wrapped bales was developed and approved by Japanese and U.S. regulatory agencies and testing procedures were evaluated in a study conducted in April 2001 (Yokoyama and Miller 2001). The first large-scale commercial test of the quarantine treatment was conducted in November–December 2001 (Yokoyama and Miller 2003). However, the bale temperatures in this test exceeded 22°C developed for standard bales and the hay export industry required lower fumigation temperatures for treatments applied during the winter in the Northwestern states. A large-scale commercial test was required to establish lower treatment temperatures and to fulfill regulatory agency testing requirements for Japan.

Our studies were conducted to ensure trade partners that new baling techniques that included large-size, fabric-wrapped bales helped prevent accidental introductions of Hessian fly and cereal leaf beetle through hay imports from the western states. For countries that required fumigations, we needed to refine the two-phase multiple quarantine treatment by establishing the fumigation temperature at <22°C to allow winter applications by exporters. Efficacy of the winter fumigation temperature needed to be confirmed in a large-scale commercial test using a large-size bale compressor at 32 kg/cm^2 and a previously untested dosage of 61 g/28.3 m^3 aluminum phosphide for 7 d. Furthermore, the effect of large-size bale compression as a single treatment on survival of Hessian fly and cereal leaf beetle needed to be evaluated for interstate hay shipments and exports.

Materials and Methods

Test and Control Insects. Hessian fly puparia were reared on wheat seedlings in flats (11 rows per flat, 28 flats) (36 by 51 by 6.5 cm, width by length by height) in a glass greenhouse at the USDA–ARS, San Joaquin Valley Agricultural Sciences Center (SJVASC), Parlier, CA, according to methods described by Yokoyama et al. (1996). The number of wheat seedlings per row in each flat is reported as the mean ± SEM of three replicates of 11 rows. Wheat seedlings infested with Hessian fly puparia were harvested by cutting the plants below the roots. Excess roots, soil, and leaves above the stems were removed.

Controls were composed from groups of wheat seedlings (0.25 row section) infested with Hessian fly puparia selected at random from 28 flats until a total of 14 rows were harvested. Each group of infested wheat seedlings was counted and placed on a pot of vermiculite saturated with water and covered with a glass cage (≈10 cm in width by 8 cm in height) (Pyrex 3250, Corning Life Sciences, Lowell, MA). Each glass-caged pot was considered a replicate (56 replicates in total), and visually examined every 1–3 d. Hessian fly adults that emerged were counted, removed by aspiration, and the number recorded. The controls were inspected in this manner until no adults were detected for nine consecutive days. The number of Hessian fly puparia per plant in the control was calculated by the total number of adults reared per plant and reported as the mean ± SEM of the replicates. The 14 rows of infested wheat seedlings used for the control were subtracted from the total number of rows used in the large-scale commercial test.

Fabric bags were sewn from two pieces (20 cm in width by 30 cm in length) of 100% nylon, pink voile. The edges of the two pieces of fabric were placed evenly together and stitched along the length on both sides and across the width in the middle to make two pouches. The top of the upper pouch was left open, and an opening was cut along the top of the lower pouch of each bag for access. Two pouches allowed even distribution of the infested wheat seedlings in the bag. Approximately 1.6 rows of infested wheat seedlings (≈233) from a flat were placed into each pouch. In total, 180 pouches were filled with 294 rows of

infested wheat seedlings. Pink flagging tape was attached to the top (122 cm in length) and bottom (30 cm in length) of the bag to facilitate placement in the bales and recovery after the test.

Large-Scale Commercial Test. The test was conducted on 17 April through 24 April 2003, in Ellensburg, WA. Procedures were similar to those described by Yokoyama et al. (1996, 1999) for standard-size hay bales and modified for use with large-sized bales (Yokoyama and Miller 2001, 2003). Copper detection plates (5 cm in width by 3 cm in height) in plastic holders as described by Storey and Hatchett (1978) were used to determine severity of exposure to PH_3 by corrosive darkening of the exposed surface. The bags containing wheat seedlings infested with Hessian fly puparia, and the separate copper detection plates were attached by flagging tape onto the top rail of a T-shaped tool made from metal pipe (≈1.9 cm in diameter). The top rail (64 cm in length) was welded perpendicular to the handle end (190 cm in length). The device was used to lower the fabric bags and copper detection plates into the chamber of a large-size bale compressor. The test materials were compressed (32 kg/cm^2 pressure) in timothy hay. Two bags were placed near each end and in the middle of each test bale (six bags per bale) and the copper plate was placed in the middle of the bale. Fifteen bales were prepared with test materials (90 bags in total, with two pouches per bag, and 15 copper plates).

Three replicate freight containers (≈2.4 by 12.2 by 2.9 m [width by length by height]; volume, 76.4 m^3) were loaded with test and nontest bales inside a building heated with propane radiant heaters (Yokoyama et al. 1996). Nine rows of large-size, polypropylene fabric-wrapped bales with six bales per row (two bales wide by three bales high) were placed into each freight container. All bales remained in the heated building before loading. Each bale containing six bags of Hessian fly infested wheat seedlings and a copper plate was placed at random in each of the following five positions in the freight container: front (row 1) top and bottom, middle (row 5), and back (row 9) top and bottom.

Temperature in the test bales and in the middle air space of the freight container were determined every 2.0 min with temperature loggers (model XTI08, Stowaway, Logan, UT) that had external thermistors (model TMC6–1T, Stowaway) on extension cables (1.8 m in length) placed in the interior of the bales through stainless steel tubing (50.8 cm in length by 4 mm i.d. by 6.2 mm o.d.) driven into drilled channels. The temperature loggers were placed in plastic bags and fastened to the bale containing the external thermistor with cloth tape. Temperature loggers and external thermistors were built with precision components by the manufacturer to meet the published specification of ±0.33 and ±0.4°C, respectively.

In addition to the temperature loggers with external thermistors, thermistor probes (11.4 cm in length; accuracy ± 0.1°C) (model ON-403-PP, Omega, Stamford, CT) were placed into the middle air space of the freight container and the side of each bale that had a temperature logger. The thermistor probes had vinyl cables that extended to the back of the freight container. The cables terminated in phone-plug connectors that extended under the door and outside of the freight container. Temperatures were monitored with a handheld thermometer (accuracy ± 0.25°C) (model 450-ATH, Omega) and recorded once each day at the same time after the test was begun. Temperatures were reported as the mean ± SEM of the replicate freight containers at 1–3 and 1–7 d.

Polyethylene gas lines to monitor fumigant concentrations (Yokoyama et al. 1999) were connected by rubber tubing to stainless steel tubing (50.8 cm in length by 4 mm i.d. by 6.2 mm o.d.) driven into bales with test materials. The gas lines were extended to the back door from the test bales in each of the five positions in the freight container and from the middle-air space. A copper plate was attached to the inside of the right, back door of the freight containers.

One large-size polypropylene fabric-wrapped bale was placed near the three freight containers and used as a control for residue analysis. Temperatures inside the heated building were monitored with a temperature and relative humidity recorder (model CT485B, Omega) and are reported as the mean ± SEM of the daily high and low temperature for 7 d.

The freight containers were fumigated in the heated building with 61 g/28.3 m^3 aluminum phosphide (Phostoxin, Degesch America, Weyers Cave, VA) for 7 d. Gas concentrations were determined each day for 7 d after the beginning of fumigation. Fumigant concentrations were determined with Dräger Phosphine 50/a tubes (Dräger, Lübeck, Germany). Concentrations were reported as the mean ± SEM of the three replicate freight containers at 1–3 d and 1–7 d.

At the end of the 7-d fumigation, the freight containers were aerated overnight, and unloaded. The test materials were removed from the bales and transported to the SJVASC for evaluation. Corrosion of copper detection plates used to visually confirm exposure to fumigant in each test bale and from the freight container door was scored as 1, light; 2, moderate; and 3, severe based on fumigant concentration, and data are reported as the mean ± SEM of the three replicates for each location.

Evaluation of Hessian Fly Survival. Infested wheat seedlings exposed to bale compression and fumigation in the large-scale commercial test were removed from the fabric bags. The infested wheat seedlings from one pouch of each bag was placed on a pot of vermiculite saturated with water, covered with a glass cage, and handled in the same manner as the unexposed controls. The presence of an adult was used as the criteria of treatment survival during a minimum 50-d evaluation period and after nine consecutive days of no adult emergence in controls. Thereafter, the infested wheat seedlings that had been exposed to compression and fumigation were examined for survivors for an additional 2 wk.

The total number of Hessian fly puparia exposed to compression and PH_3 fumigation in the three replicate freight containers in the large-scale test was calculated

by multiplying the number of wheat seedlings used in the large-scale commercial test by the number of Hessian fly adults reared per plant in the control.

Residue Analysis. Three samples of hay (≈100 g per sample) were collected at random from bales containing test materials in the front, middle, and back locations in each of the three replicate freight containers after aeration and during recovery of test materials. Three samples of hay also were collected from the nonfumigated control bale that was kept with the freight containers in the heated building. The samples were placed in glass jars (9 cm in diameter by 17.1 cm in height) and covered with a metal lid (8.6 cm in diameter) that had a 1.3-cm-diameter septum installed through a hole in the lid. The septum was sealed in place with silicone adhesive. The lid was fastened to the jar with a metal screw-on collar. The samples were transported to the SJVASC and frozen until used for residue analysis.

PH_3 residues were determined by gas chromatography using methods similar to those described by Yokoyama et al. (1994b). The gas chromatograph (model CP3800, Varian, Walnut Creek, CA) was equipped with a pulsed flame photometric detector. The column was a megabore, ultimetal (0.53 mm by 12.5 m) with CP-PoroPlot Q phase, and a 2.5-m particle trap (Varian). Temperatures for the injector, oven, and detector were 250, 75, and 300°C, respectively. The helium gas flow rate was 11.4 ml/min, and the make-up gas flow rate was ≈9 ml/min. Headspace gas samples were collected through the septum of each jar of hay samples with a gastight syringe, and injected into the gas chromatograph by using an integral gas-sampling valve with a 0.25-ml loop. Retention time for PH_3 was ≈0.78 min. Fumigant concentrations were reported as the mean ± SEM of three replicates of three determinations per location in the freight container after overnight aeration.

Compression of Hessian Fly. In 2003, bags containing wheat seedlings infested with Hessian fly puparia (≈470 per bag) were introduced into a large-size bale compressor (32 kg/cm^2 pressure) and compressed in timothy hay in Ellensburg, WA. Two bags were placed near each end and in the middle areas of each test bale (six bags per bale). Four bales were compressed with 24 bags in total with two pouches per bag. The bags were recovered after compression and the infested wheat seedlings from one pouch of each bag was placed on vermiculite saturated with water in a pot, covered with a glass cage, and handled in the same manner as the unexposed controls. Controls were made from the same harvested and infested wheat seedlings that were used in compression tests. Approximately 35 wheat seedlings were placed on water-saturated vermiculite in each pot (n = 44) and covered with a glass cage. Adult emergence was monitored until adults did not emerge in all cages (≈49 d). Thereafter, cages were inspected for adults for an additional 7 d.

In 2004, using the same procedures in the 2003 test, eight large-size bales were compressed with 48 bags in total. Controls were composed of 27 seedlings in each glass-caged pot (n = 44). Adults were monitored in the same manner as the previous test except emergence occurred for a longer period (≈83 d). The number of adult survivors among the three bale positions was compared in both tests using a one-way analysis of variance (ANOVA) and Tukey's honestly significant difference (HSD) test (GraphPad Software 2007), and data are reported as mean ± SEM percentage of survival.

Table 1. Mean ± SEM number of infested wheat seedlings per row, adults reared in controls, and the total number of Hessian fly puparia in a large-scale commercial test

No. plants per row[a]	No. adults per plant[b]	Total no. puparia[c]
145.8 ± 6.4	1.07	45,366

[a] Three replicates of 11 rows.
[b] Number of adults in the control (n = 1,897) reared per plant in 56 replicates of infested plants (≈32 mean plants per replicate; n = 1,777) harvested in 0.25-row sections at random from ≈14 rows.
[c] Number of wheat seedlings per row multiplied by 290.8 rows (294 total rows minus 3.2 rows not compressed in the test) in three replicate freight containers, multiplied by the number of adults reared per plant in the controls.

Compression of Cereal Leaf Beetle. Cereal leaf beetle adults were collected (45° 39′ N, 123° 8′ W) from oat and wheat fields 4.4 km northwest of Banks, OR, on 11 July 2004. The insects were collected in sweep nets, transferred to 480 ml (9 cm in diameter by 9.7 cm in height) paper cartons (n = 47), covered with cotton organdy, and a water-moistened sponge placed on the top. The cartons were placed in insulated chests with ice and transported to a work area. The next day, the adults were placed in bags with two pouches as described for tests with Hessian fly. The adults were evenly distributed between the two pouches per bag and among 45 bags. Four of these bags were used for noncompressed controls. The bags of cereal leaf adults were introduced into a large-size bale compressor (32 kg/cm^2 pressure) and compressed in timothy hay in Aurora, OR. Two fabric bags were placed near each end and in two middle areas of each test bale (eight bags per bale). Five bales were compressed with eight bags per bale, and one bale was compressed with one bag in the middle area (41 bags in total with two pouches per bag). Bags containing cereal leaf beetle adults in controls and in bags recovered after compression were inspected for live adults. Insects showing movement were considered alive. Data are reported as mean ± SEM percentage of survival.

Results

Large-Scale Commercial Test. The total number of Hessian fly puparia tested in large-size, polypropylene fabric-wrapped bales in three replicate freight containers in the large-scale commercial test was 45,366 (Table 1). The total number was calculated by the total number of infested wheat seedlings used in the test (42,398) multiplied by the number of Hessian fly adults (1.07) reared per plant in the controls. One fabric bag with two pouches of ≈3.2 rows of infested

Table 2. Mean ± SEM copper detection plate values, temperatures, and fumigant concentrations in different locations in freight containers containing large-size polypropylene fabric-wrapped bales of timothy hay exposed to compression (32 kg/cm^2) and fumigation (61 g/28.3 m^3 aluminum phosphide for 7 d at 20°C) to control Hessian fly in a large-scale commercial test

Location	No. adults	Copper plate value[a]	3 d		7 d	
			Temp[b] (°C)	PH_3 concn[c] (ppm)	Temp[b] (°C)	PH_3 concn[c] (ppm)
Front-top	0	2 ± 0	17.1 ± 0.5	238.3 ± 112.6	17.7 ± 0.3	367.1 ± 95.8
Front-bottom	0	2 ± 0	15.7 ± 0.2	207.8 ± 100.9	16.2 ± 0.2	327.8 ± 89.0
Middle-bale	0	2 ± 0	15.8 ± 0.2	274.4 ± 114.8	16.1 ± 0.2	388.8 ± 91.6
Middle-air	0	2 ± 0	15.7 ± 0.3	320.0 ± 119.7	16.2 ± 0.2	460.9 ± 105.4
Back-top	0	2 ± 0	18.5 ± 0.5	340.0 ± 106.7	18.5 ± 0.2	453.6 ± 88.1
Back-bottom	0	2 ± 0	17.9 ± 0.3	306.1 ± 102.2	18.0 ± 0.1	428.6 ± 89.9
Door		2 ± 0				

[a] Three replicates of degrees of corrosion: 1, light; 2, moderate; and 3, severe.
[b] Three replicates of 720 determinations per day with temperature loggers with external thermistors in the interior of the bale.
[c] Three replicates of one determination per day.

wheat seedlings located in the back bottom bale of the third replicate freight container, did not enter the compression chamber and was removed from the test. Therefore, this number of rows of infested wheat seedlings was deducted from the total number used in the test (Table 1). Approximately 15,122 Hessian fly puparia were tested in each freight container. No Hessian fly puparia survived the large-scale commercial test (Table 2). Furthermore, no adults emerged from infested wheat seedlings exposed to compression and fumigation for an additional 2 wk after the 59-d evaluation period.

Copper plates are used by trade partners to visually verify fumigation of hay bales in freight containers. Copper plate corrosion values of two inside the doors, and in the middle of the large-size bales in all locations in the three freight containers indicated moderate exposure to PH_3 during the test (Table 2). The mean ± SEM of the lowest and highest daily temperature in the heated building over 7 d was 16.3 ± 0.4°C. Temperatures in different locations in the freight container for the first 3 d and during the entire 7 d fumigation are shown in Table 2. The daily temperatures for 1–3 d (mean ± SEM) recorded with thermistor probes and a handheld thermometer were as follows: front-top, 17.4 ± 0.4; front-bottom, 16.5 ± 0.4; middle-bale, 17.1 ± 0.4; middle-air, 15.1 ± 0.3; back-top, 18.5 ± 0.3; and back-bottom, 17.9 ± 0.3. The 1–7 d (mean ± SEM) daily temperatures were as follows: front-top, 17.8 ± 0.2; front-bottom, 17.0 ± 0.2; middle-bale, 17.3 ± 0.2; middle-air, 15.7 ± 0.3; back-top, 18.5 ± 0.1; and back-bottom, 18.1 ± 0.1. These handheld thermometer temperatures were similar to those recorded by temperature loggers in Table 2. The temperatures during the test resulted in complete mortality of Hessian fly puparia and were below 20°C proposed for the quarantine treatment.

Fumigant concentrations in large-size, polypropylene fabric-wrapped bales are shown in Table 2. Highest mean concentrations of PH_3 were observed after 7 d of fumigation in all locations in the freight containers. Mean fumigant concentrations ranged from 208 to 340 ppm during the first 3 d and ranged from 328 to 461 ppm after 7 d of fumigation. PH_3 residues after fumigation and aeration ranged from 4 to 9 ppb in three locations in the freight containers (Table 3).

Compression Tests. The number of Hessian fly puparia compressed was 3,468 and 24,344; adults emerging in controls was 0.3 and 1.6 per plant; and survival was 3.6 and 3.0% in 2003 and 2004 tests, respectively. The number of survivors in each bale position was not significantly different (Table 4). The total number of cereal leaf beetle adults was 2,512 compressed and 353 noncompressed resulting in 0 and 98.3% survival, respectively.

Discussion

The results of the large-scale commercial test fulfilled testing requirements and confirmed the efficacy of compression (32 kg/cm^2) and fumigation (61 g/28.3 m^3 aluminum phosphide for 7 d at 20°C) to control Hessian fly in large-size, polypropylene fabric-wrapped bales of hay. The research was approved by Japanese and U.S. regulatory agencies and export regulations were implemented on 20 May 2005. The quarantine treatment is available for use with other species of hay and other export markets.

Exporting hay in large-size, polypropylene fabric-wrapped bales, ≈54 per freight container, is more economical than exporting ≈416 compressed standard bales in the same size container. Time and handling costs and the need for specialized vehicles are greatly reduced during the loading and unloading process. The large-size bale wrapper also provides a sanitary packaging method that also prevents debris from contacting the product. Timothy hay was used in the large-scale commercial test as the representative species for all other hays to be exported to Japan by this method.

Table 3. Mean ± SEM hydrogen phosphide residues after fumigation (61 g/28.3 m^3 aluminum phosphide for 7 d) and overnight aeration in large-size polypropylene fabric-wrapped bales of timothy hay in different locations in freight containers in a large-scale commercial test

Location	Fumigant concn (ppb)
Front-row	4.32 ± 1.22
Middle-row[a]	8.38 ± 2.19
Back-row	9.13 ± 1.28
Control	<1

[a] Replicate 1, two samples.

Table 4. Mean ± SEM percentage survival of Hessian fly puparia and cereal leaf beetle adults after compression in different positions in large-size bales of timothy hay

Yr	Species	No. insects	% survival	Position in bale		
				Front	Middle	Back
2003	Hessian fly	3,480	3.6	7.1 ± 0.5a	10.0 ± 1.6a	4.8 ± 1.8a
2004	Hessian fly	24,344	3.0	3.9 ± 1.6a	2.8 ± 2.0a	11.4 ± 10.0a
2004	Cereal leaf beetle	2,512	0	0	0	0

Means followed by the same letter in each row are not significantly different ($P > 0.05$, Tukey's HSD test; GraphPad Software 2007).

The hydraulic ram used in these tests, compresses hay in three to five strokes into a large-size bale after the hay has been passed through a slicing grid. The amount of pressure (32 kg/cm^2) used to make the large-size bale is less than the amount of pressure (80 kg/cm^2) used to make compressed standard bales (Yokoyama et al. 1999), but it is greater than the amount of pressure (0.21 kg/cm^2) required to destroy Hessian fly puparia (Yokoyama et al. 1993a). The multiple strokes of the hydraulic ram needed to make a large-size bale may enhance destruction of the puparial stage. The infested wheat seedlings that were removed from the fabric bags at the end of the large-scale commercial test were severely damaged by compression and similar in appearance to infested wheat seedlings exposed to standard bale compressors.

Highest mean temperatures were observed in bales in the back-top and bottom of the freight containers (Table 2), but they did not exceed the proposed fumigation temperature of 20°C. The test was conducted during cold weather and use of the heated building enabled fumigation at the proposed dose of 61 g/28.3 m^3 aluminum phosphide for 7 d at 20°C, and ≈24 h overnight aeration. Fumigations above 20°C would be allowed in certified fumigation facilities implementing the quarantine treatment but not temperatures below 20°C because reduced gas diffusion and insect metabolism may reduce insect control (Storey and Hatchett 1978).

The amount of corrosion observed on copper plates inside the large-sized bales in this test (Table 2) are the same as reported for compressed standard bales by Yokoyama et al. (1999). A fumigant dose of 60 g/28.3 m^3 is currently used in the approved quarantine treatment for compressed standard bales. Aluminum phosphide tablets (one tablet releases 1 g of PH_3) can be purchased in 33 tablet packages and a dose of 61 g/28.3 m^3 would eliminate the need to subdivide the packages for a 76.4-m^3 freight container. Yokoyama et al. (1994b) reported that Hessian fly response was similar at dosages of >60 g/28.3 m^3 aluminum phosphide for 3 d in laboratory tests. A mixture of 2% PH_3 and 98% CO_2 dispensed from gas cylinders was found to shorten the fumigation time to <48 h for stored-product pests (Hartsell et al. 2005). In an earlier study, a 3-d PH_3 fumigation for Hessian fly in standard bales was proposed by Yokoyama and Miller (2003). A procedure to shorten the fumigation period would reduce handling and transport expenses including freight container rental costs.

The fumigant concentrations observed in this large-scale commercial test with large-size, polypropylene fabric-wrapped bales (Table 2) were lower during the first 3 d and higher after 7 d than in the previously reported test (Yokoyama and Miller 2003) that ranged from 367 to 425 and from 253 to 407, respectively. Fumigation temperatures in this test were lower and did not fluctuate as in the previous test, producing a slow increase and sustained concentration of fumigant in the freight containers that probably supported high insect mortality.

PH_3 residues (Table 3) were below the U.S. Environmental Protection Agency tolerance of 0.1 ppm in animal feeds (Degesch America 2000). The residues were slightly higher in some individual samples than in the previously reported test (<10 ppb) (Yokoyama and Miller 2003), and they were probably related to the higher sustained fumigant concentrations at the lower temperatures used in this test. Based on our results, hay that is compressed and fumigated in large-size, polypropylene fabric-wrapped bales is safe for use as animal feed.

Large-size bale compression was shown to be highly effective technique to control Hessian fly puparia and cereal leaf beetle adults (Table 4). The occurrence of either pest is highly unlikely in exported hay due to quality control during field production and a rigorous selection process before harvest. Furthermore, we tested extraordinarily high numbers of insects to fulfill regulatory agency requirements to confirm treatment efficacy. Only low numbers of Hessian fly puparia survived in both tests and compression alone was sufficient to kill all cereal leaf beetle adults. Standard bale compression was proposed as a single treatment to control cereal leaf beetle larvae (Yokoyama and Miller 2002) and Hessian fly puparia (Tabil et al. 2006). Although large numbers of Hessian fly were not completely controlled by large-size bale compression in this study or by standard bale compression in previous studies (Yokoyama and Miller 1993b), Yokoyama and Miller (1994a) found that Hessian fly did not survive hay harvesting and postharvest handling procedures. Thus, complete control of these regulated pests could be achieved in a systems approach that combined field handling practices and hay processing plant procedures to reduce pest numbers.

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