Technical Note

Evaluation of Kiln Heating as a Phytosanitary Treatment for *Ceratocystis*-Infested ʻŌhiʻa (*Metrosideros polymorpha*) Wood

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Abstract

Phytosanitary heat treatments of *Ceratocystis lukuohia and Ceratocystis huliohia*-colonized *Metrosideros polymorpha* wood were evaluated using kilns. Wood poles subjected to a 22- to 34-day dehumidification kiln schedule with a heat treatment to 60°C to the poles' core. In vacuum kiln trials, logs were heated to 56°C at 70 percent log radius depth and the temperature maintained for 30 minutes. Neither *Ceratocystis* species was isolated from heat-treated wood using carrot baiting, whereas both fungi were isolated from control logs held at ambient temperature. Results of this study offer kiln-heating as a way to eradicate *Ceratocystis* fungi from *M. polymorpha* wood.

ʻŌhiʻa (*Metrosideros polymorpha*) is Hawaiʻi's most ecologically significant and culturally valuable native hardwood tree species (Mueller-Dombois et al. 2013). The wood is a highly valued local timber product used for decorative pillars, posts, railings, and flooring, whereas unprocessed material is used for firewood and traditional woodworking (Skolmen 1974). As a commodity for local architecture, the wood is generally sold as green, untreated, debarked logs and it comprises a significant portion of the local milling industry. Unfortunately, the native forests once dominated by ʻōhiʻa are now threatened by rapid ʻōhiʻa death (ROD), a complex of two diseases caused by the nonnative fungal pathogens *Ceratocystis lukuohia* and *Ceratocystis huliohia* (Barnes et al. 2018, Juzwik et al. 2019a, Hughes et al. 2020). These fungi were newly discovered in association with a widespread mortality of ʻōhiʻa of unknown origin in the Puna and South Hilo District of Hawaiʻi Island in the 2010s (Keith et al. 2015, Barnes et al. 2018). Both fungi are currently only known to infect ʻōhiʻa. Of the two species, *C. lukuohia* is more aggressive and responsible for the majority of widespread ʻōhiʻa mortality and downstream ecological impacts to native forests (Mortenson et al. 2016, Camp et al. 2019, Fortini et al. 2019, Hughes et al. 2020). In particular, ʻōhiʻa-dominated forests comprise the majority of the state's watersheds and ROD can lead to accelerated native forest degeneration, replacement by invasive plants, and reduced freshwater supply (Povak et al. 2017).

As of July 2022, both *C. lukuohia* and *C. huliohia* are only present on Hawaiʻi Island and Kauaʻi; however, there is concern about the movement of *C. lukuohia* to noninfected islands via the wood trade as some *Ceratocystis* fungi can remain viable in infected wood for several months to years (Tsopelas et al. 2017). Most commercial ʻōhiʻa wood is harvested on Hawaiʻi Island and is sold and transported as debarked, air-dried logs. To respond to this threat, statewide quarantine restrictions of ōhiʻa products were established in 2016 and products originating from infected islands are required to undergo diagnostic testing for *C. lukuohia* and *C. huliohia* contamination before

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shipment (Hawai‘i Department of Agriculture, amendment to chapter 4-72, amendment §4-72-13; Heller and Keith 2018). These restrictions led to extra logistical costs and complexities to mill owners, nearly eliminating ‘ōhi‘a demand and production. Log screening uses a molecular assay (quantitative polymerase chain reaction [qPCR]) to detect *Ceratocystis* deoxyribonucleic acid (DNA) in the wood (Heller and Keith 2018), and although highly sensitive, every outgoing log must be individually screened, resulting in a laborious and costly process for diagnosticians and regulators. There is an urgent need for an effective and practical phytosanitary treatment that can effectively treat ‘ōhi‘a wood.

Recognized approaches for phytosanitary treatments of wood include debarking, fumigation, drying, heat (including irradiation), and chemicals (Morrell 1995, Allen et al. 2017). In a previous study with ‘ōhi‘a, submersion in a 15 percent borate solution and a 10-week drying/diffusion period reduced *C. lukuohia* viability in 1-m-long bolts, but did not completely eliminate the pathogen (Hughes et al. 2021). Vacuum steam treatment has been effective in eliminating tree pathogenic fungi from oak and walnut logs (Juzwik et al. 2019b, 2021). The same portable vacuum steam unit that successfully treated oak and walnut logs was shipped to Hawai‘i to test large-diameter ‘ōhi‘a logs (24 to 43 cm in diameter), and heating to 60°C for 60 minutes to a depth of 70 percent of the log radius completely eradicated ROD fungi (Juzwik et al. 2022). However, the forest and wood products industry in Hawai‘i consists of small, locally owned businesses and a vacuum steam unit is currently unavailable for treating wood. To develop a phytosanitary treatment that can be quickly incorporated into the state’s biosecurity regulatory framework, we focused on the infrastructure currently available.

A commercial dehumidification kiln and a vacuum drying kiln located at mills on Hawai‘i Island presented the authors with opportunities to evaluate the efficacy of kiln heating to eliminate viable ROD *Ceratocystis* pathogens from colonized roundwood. As there are few kilns on the island, the two used in this study represent a large portion of overall capacity to treat wood. Both types of kilns are used for drying wood to specific moisture content (MC) levels depending on product use. A heat pump is used to remove water from wood treated in a dehumidification kiln. This system allows for recycling of heat within the kiln box compared with exhausting the evaporated water and heated air outside as with a conventional drying kiln. With the dehumidification kiln, humid air is passed over a cooling coil where water condenses, and the cool water is drained outside the kiln while the heated air is recirculated. This recirculation of hot air can result in within-kiln air temperatures $\geq$72°C, which exceeds the 56°C and 60°C temperatures known to kill fungal pathogens in wood (Ramsfield et al. 2010; Mayfield et al. 2014; Juzwik et al. 2019b, 2021, 2022).

Vacuum-drying kilns rely on reduced atmospheric pressure to create water vapor at a lower temperature (e.g., 85°C) than that of the dehumidification kiln. Thus, drying times for lumber are much less than those for conventional and dehumidification kilns. However, heat must be continuously applied to wood in a vacuum kiln. Furthermore, the vacuum chambers of such kiln systems are small compared with larger kiln boxes used with dehumidification and conventional kilns. Internal wood temperature thresholds (56°C and 60°C) are commonly used to eradicate wood-inhabiting insect pests in firewood and wood-packing material in the United States and thus were our target threshold temperatures to be evaluated in trials with dehumidification and vacuum drying kilns (International Plant Protection Convention 2006, National Plant Board 2020).

The main objective of this research was to test kiln heating for its ability to eradicate viable *C. lukuohia* and *C. huliohia* from debarked ‘ōhi‘a roundwood using dehumidification and vacuum drying kilns. The treatment conditions and schedules evaluated would then offer the local mills a baseline for potentially incorporating phytosanitary treatments of ‘ōhi‘a roundwood in their offered services.

Materials and Methods

Tree selection and inoculation

The following studies occurred over a 2-year period from 2018 to 2020. For the 2018 dehumidification kiln trials, 30 *M. polymorpha* trees (6.0 to 10.8 cm diameter at breast height [DBH]) were selected from the Hilo Forest Reserve (19°41.782′N, 155°13.309′W) and for the 2019 vacuum kiln study; 19 trees (20 to 32 cm DBH) were selected from the Waiākea Forest Reserve (19°37.361′N, 155°06.297′W), both on the east side of Hawai‘i Island near Hilo. Both sites had documented ROD mortality for several years (Vaughn et al. 2018). The trees were numbered with circular metal tags and a 3-m-long section along the main stem was demarcated with spray paint to indicate the future log to be harvested. For both trials, the trees were artificially inoculated by applying a fungal agar slurry to stem wounds as previously described by Hughes et al. (2020). Two wounds on the lower stem of trees were inoculated with the systemic wilt pathogen, *C. lukuohia*, whereas four wounds at increasing stem heights were inoculated with the canker pathogen, *C. huliohia* (Juzwik et al. 2019a). The *C. lukuohia*-inoculated wounds were 60 cm (for dehumidification trials) or 138 cm (for vacuum kiln trials) above the log bottom demarcation line, on opposite sides of the stem. In contrast, the four wounds receiving *C. huliohia* were made between 60 cm and 240 cm above the log bottom demarcation line with 60 cm vertical spacing between each wound placed in a spiral manner around the tree stem, thus allowing for formation of multiple cankers. After application of fungal inoculum to the sapwood, bark plugs were replaced over the inoculated wounds and sealed with duct tape.

For the 2018 dehumidification kiln study, a single fungal isolate was used for inoculum (*C. lukuohia*, P14-1-1; *C. huliohia*, P16-8). For the first experiment 12 trees were inoculated in April; an additional 18 trees were inoculated for the second experiment in June. In total 30 trees were inoculated, 15 trees per each *Ceratocystis* species. For the 2019 vacuum kiln trials a mixture of two fungal isolates was used per *Ceratocystis* species (*C. lukuohia*, P14-1-1 and P16-7; *C. huliohia*, P15-59 and P16-8). Inoculum production and methods were the same as mentioned above. To allow for more time for internal fungal colonization of *C. huliohia*, 13 trees were inoculated in August and *C. lukuohia* inoculations occurred in September (6 trees).

Tree felling and log preparation

Study trees were felled 70 and 100 days after inoculation for the first and second dehumidification kiln trials (2018),

respectively, and 119 (*C. lukuohia*) and 147 (*C. huliohia*) days after inoculation for the 2020 vacuum kiln trials. For this study, the smaller-diameter main stems (≈8-cm large-end diameter) used in the dehumidification kiln trials are referred to as poles and the thicker main stems (≈20- to 25-cm large-end diameter) of the vacuum kiln trials are referred to as logs. After felling, side limbs were removed, poles were cut to a length of 3.0 m (dehumidification kiln trial) and logs to 2.45 m (vacuum kiln trial), and all wood was transported to the US Department of Agriculture (USDA) Agricultural Research Service (ARS) Pacific Basin Agricultural Research Center (PBARC) in Hilo for processing. The bark was removed by draw knife to the outer sapwood, and poles and logs were shortened to approximately 2.6 m (dehumidification kiln trial) and 2.0 m (vacuum kiln trial), respectively. A 4-cm-thick disk was removed from one of the logs' (vacuum kiln) or both poles' ends (dehumidification kiln) to assess pretreatment wood MC. To determine pretreatment *C. lukuohia* viability in ʻōhiʻa wood, an additional 4-cm-thick disk of symptomatic (discolored) wood was removed from each pole/log end (two per wood length; Fig. 1A), labeled, and held in a cold room at 5°C until further processing. For *C. huliohia*-inoculated wood, sampling occurred in the areas adjacent to the inoculation points where staining associated with fungal colonization was most evident. Thus, four disks were removed per log for pretreatment fungus viability assays and held at 5°C (Fig. 1B). Final pole lengths for the dehumidification kiln trials were 2.5 m for *C. lukuohia*-inoculated wood and slightly shorter (2.1 m) for *C. huliohia*-inoculated wood as pretreatment viability samples were collected near the area with vascular staining. Vacuum kiln logs were at a final length of 1.7 m. The ends of the reduced-length wood sections were painted with liquid paraffin sealant (Clear Multi-Surface Waterproofer, Thompsons WaterSeal, Cleveland, OH or Anchorseal, Anchor-Seal Inc., Gloucester, MA) to minimize heat infiltration through the cut ends. Poles/logs were labeled with circular metal tags.

Wood temperature, moisture monitoring, and drying schedules

Temperatures at the pole/log surface and within the wood were monitored in real time using thermocouple wires and data loggers to determine start of threshold temperature exposure timing. For each dehumidification kiln trial, three *C. lukuohia*- and three *C. huliohia*-infested ʻōhiʻa poles (six total per kiln charge) were drilled in the base of the pole end and to the geometric center, thermocouple wires inserted, and each hole filled with plumbers' putty to prevent unwanted steam intrusion into the hole (Chen et al. 2017). A separate thermocouple wire was left on top of the pile of poles to monitor ambient air temperature within the kiln. All thermocouple wires in the kiln were fed outside via a small polyvinyl chloride conduit pipe (backfilled with foam) to two data loggers (Hobo, Onset Computer Corp., Bourne, MA). One *C. lukuohia*- and one *C. huliohia*-inoculated pole (two total) with thermocouple wires were held outside the kiln at ambient temperatures as unheated negative controls for the June trial and two poles per fungal species (four total) for the September trial.

For each kiln charge of the 2020 vacuum kiln study, three logs were selected for temperature monitoring. Per log, three holes were drilled into wood at radial depth of 70 percent toward the log's core at ⅓, center, and ⅔ of the log length. Another hole was drilled to the geometric center and one through the cut face of the log. Omega K-type thermocouple wires were inserted into the holes, the holes filled with plumbers' putty, and a single thermocouple placed on a log exterior to monitor ambient temperatures inside the kiln box. Thermocouple wires exited the kiln chamber via a sealed port to an outside computer data acquisition system (LabVIEW, National Instruments Corp., Austin, TX) for data collection and real-time thermal monitoring. A single log per fungal species with thermocouple wires was held outside the kiln at ambient temperatures per each vacuum kiln trial as a negative control. For the three vacuum kiln trials conducted, two drying schedules were used. For the first trial, the heating schedule was designed to kill *Ceratocystis* fungi by reaching the 56°C target temperature at a radial depth of 70 percent toward the core and then the vacuum drying process was initiated. For the second and third trials, the heating schedule was designed to increase the temperature more slowly to the targeted 56°C during the vacuum drying cycle (combining the heating and drying cycles).

For all trials with both kiln types, internal temperatures of logs were monitored to determine the time when the threshold temperature was reach for each kiln load. Wood MC was assessed from a subsample of each pole or log before and after heat treatments using an oven-drying method (Eckelman 1997; Fig. 1). To obtain wood MC, a 4-cm-thick disk (or a representative portion) was immediately weighed after cutting and placed into a drying oven (105°C) until a constant weight was obtained. Dry-basis wood MC was determined as (Eckelman 1997):

$$\frac{\text{Wet weight} - \text{dry weight}}{\text{dry weight}} \times 100\%$$

Kiln heating treatments

Log treatments were conducted using commercial equipment at local mills in Hilo and Waimea, Hawai'i Island. For the 2018 trial, a dehumidification kiln (High Temperature DH System, Nyle Systems LLC, Brewer, ME) was used. ʻŌhiʻa poles were placed on top of a commercial load of stickered hardwood flooring planks milled on site. The kiln operator made gradual temperature increases on the basis of his experience and knowledge. Once the target temperature of 60°C at the core for all thermocouple-monitored poles ($n = 3$ in each trial) was achieved, the temperature was held constant for a minimum of 5 hours. The kiln was then shut off and doors opened when the operator deemed it appropriate (to avoid wood warping or splitting). For the first trial (June 2018), poles from five *C. lukuohia*- and *C. huliohia*-inoculated trees each were placed in the kiln for heat treatment, with two ambient negative controls (12 poles total). For the second trial (September 2018), seven poles were placed in the kiln and two poles were held outside as ambient controls per fungal species (18 poles total). In total, 24 *Ceratocystis*-infested poles were kiln-treated along with six nonheated negative controls (30 poles for both trials combined).

A steam-heat-operated continuous vacuum kiln (iDry Standard, iDRY LLC, Barre, VT) with a solar-augmented (preconditioning) water-heating device was used to treat *M. polymorpha* logs (≈20- to 25-cm large-end diameter) in late January–early February 2020. Components of the system

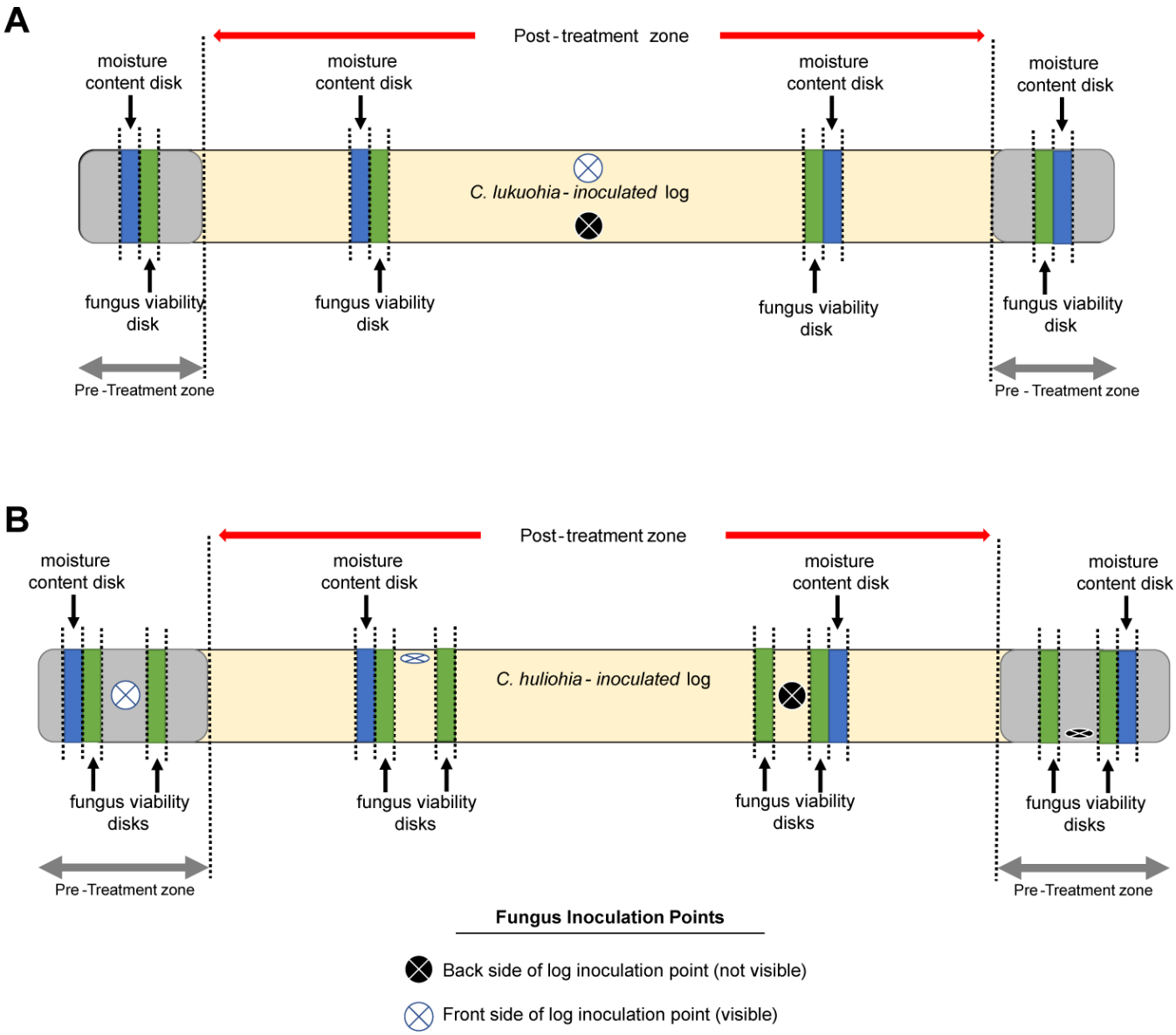

Figure 1.—Schematic for obtaining wood disks (4 cm thick) for moisture content and Ceratocystis *viability carrot-baiting assays from* Metrosideros polymorpha *wood lengths inoculated with (A)* Ceratocystis lukuohia *or (B)* Ceratocystis huliohia.

were a vacuum chamber, vacuum pump, water boiler, and control system. The chamber dimensions were 1.7 m wide by 1.7 m high by 4.3 m long. When all monitored logs reached 56°C at a radial depth of 70 percent to the core, the load was held for 30 minutes. Three trials (kiln charges) were conducted, but rate of heat increase and number of drying cycles differed between Trial 1 and Trials 2 + 3 to determine effects on total time required and resulting wood MC. Trial 1 used a test schedule to kill the *Ceratocystis* spp. in the logs and achieve a fast vacuum drying rate (referred to as kill + dry schedule); Trials 2 + 3 only focused on killing *Ceratocystis* and did not try to optimize log drying (referred to as kill-only schedule). In the first trial using the kill + dry schedule, five *C. lukuohia*- and *C. huliohia*-inoculated logs (10 total) were heated in the kiln with a single log per fungus species left outdoors (ambient temperature) under shade beside the kiln chamber to serve as negative controls (2 total). In the second (*C. lukuohia* logs only) and third (*C. huliohia* logs only) trials using the kill-only schedule, five logs were heated per kiln charge, with a single log serving as an ambient temperature control for each trial. In total, 20 *Ceratocystis*-infested logs were kiln treated and four nonheated *Ceratocystis*-infested logs served as negative controls (24 logs for both trials combined).

Posttreatment and Ceratocystis viability testing

After treatment, the thermocouple wires were removed and the logs were transported back to the USDA PBARC facility. For *C. lukuohia*-inoculated trees, log end segments (22 cm) were removed and discarded. Four 4-cm-thick disks were removed per log end with two used to assess posttreatment MC levels and two to assess *Ceratocystis* viability (Fig. 1A). For *C. huliohia*-inoculated trees, three disks were removed per log end, with two used for fungus viability assays and one for MC determination (Fig. 1B).

Disks for pre- and posttreatment *Ceratocystis* viability testing were bagged and stored at 5°C.

Small sapwood chips were obtained with a chisel and mallet and used for carrot baiting (Moller and DeVay 1968). For the smaller-diameter poles of the dehumidification kiln study, two radial depths of up to 1.0 cm (outer zone) and 1.1 to 2.0 cm (inner zone) were sampled. For the larger logs from the vacuum kiln, the assayed zones were 0.5 to 2.5 cm (outer) and 3.0 to 5.0 cm (inner). On the basis of wood disk circumference, four (90° apart) and six (60° apart) regions around the disk were subsampled for the dehumidification and vacuum kiln studies, respectively. Control logs were treated in a similar manner. To bait *Ceratocystis* fungi, the excised wood chips were sandwiched between two carrot discs (approx. 0.5–1.0 cm thick), wrapped in laboratory film (Parafilm, Bemis Co., Neenah, WI), individually bagged, and incubated at ambient temperatures (≈24°C) for up to 30 days (Hughes et al. 2021). Baits were rated positive for viable *Ceratocystis* growth when grayish mycelia and fruiting bodies (perithecia) were visible on wood chips or carrot surfaces. For those baits in which perithecia did not fully mature, a qPCR detection assay was used to confirm the pathogen(s) from excised carrot bait pieces (Heller and Keith 2018). To validate the accuracy of our *Ceratocystis* visual identifications, a subsample of positive carrot baits was assayed using qPCR as described above ($n = 56$ total).

Results and Discussion

Wood temperature, MC monitoring, and drying schedules

For the 2018 dehumidification kiln, the first trial lasted a total of 22 days (526 total h), and logs were heated to 60°C at their core for 10 hours (Fig. 2A). In the second kiln trial, an unexpected loss of power occurred, and the kiln remained closed until the proper components were obtained and a service technician was able to restore function. This resulted in a longer than usual run time of 34 days (812 h in kiln). Poles were exposed to 60°C at their core for 5 hours (Fig. 2B). Core temperatures of the control poles oscillated from 21 to 29°C and 23 to 32°C for the first and second trials, respectively (Fig. 2). Once the target temperature was reached for each trial, the kiln was shut off and allowed to cool before wood was removed. Initial ʻōhiʻa wood MC was 75 to 77 percent and 81 to 83 percent for the first and second trials, respectively. Dehumidification kiln treatment reduced the wood MC to approximately 14 to 16 percent, whereas natural drying of control poles stored under ambient conditions resulted in a MC of 30 percent (data not shown).

For the first 2020 vacuum kiln trial using the kill + dry schedule, log temperature increased rapidly over 14 hours to 56°C at the target 70 percent radial core depth and the kiln was held at that log temperature for 30 minutes (Fig. 3A). The temperature was then lowered to approximately 47°C and held for additional vacuum cycles for 95 hours to provide some drying of the wood (4.5 days/110 h in kiln). For Trials 2 and 3 using the kill-only schedule, the temperature component of the treatment schedule was increased more slowly (over ~48 h) until 56°C was reached at the targeted wood depth with minor emphasis on drying the wood (Fig. 3B). Wood for the vacuum kiln trials had initial MC values ranging from 73 to 89 percent. In the first trial, where drying was of interest, logs remained at 68 percent MC, whereas in the latter two trials, where drying was not a focus, logs retained a MC of 74 to 76 percent (data not shown).

Dehumidification kiln trials of Ceratocystis viability

For both the first and second trials, viable *C. lukuohia* was recovered onto carrot baits in 94 to 100 percent of wood samples ($n = 240$) before kiln heating treatments (Table 1). *Ceratocystis huliohia* was recovered in 76 to 99 percent of carrot baits ($n = 240$). For both pathogens, the fungus was isolated more often from the outer sapwood zones than the inner (Table 1). In comparison, viable *Ceratocystis* species were never detected in carrot baits from kiln-heated wood samples ($n = 384$, data not shown). The negative control poles held outside the kiln under shade at ambient temperatures for a mean of 28 days commonly yielded the pathogens. Specifically, *C. huliohia* was isolated in 65 percent and *C. lukuohia* in 96 percent of carrot baits ($n = 48$ per fungal species) on the basis of three poles per species. All visually positive carrot-bait subsamples taken for qPCR validation were positive and congruent with the inoculated *Ceratocystis* species (data not shown). Thus, the dehumidification kiln treatments were successful in eradicating viable *Ceratocystis* propagules from the colonized poles. Like our previous work with a vacuum–steam unit, a threshold temperature of 60°C eradicated *C. lukuohia*, *C. huliohia* and the oak and walnut pathogens *Bretziella fagacearum* and *Geosmithia morbida*, respectively (Juzwik et al. 2019b, 2021, 2022). The current standard of 60°C for 60 minutes (heat treatment standard T314-a) was accepted for treating ash (*Fraxinus* spp.) firewood in quarantined areas of the United States against the heat-tolerant emerald ash borer (*Agrilus planipennis*; Myers et al. 2009, National Plant Board Firewood Guidelines 2020, USDA Treatment Manual 2022).

Vacuum kiln trials of Ceratocystis viability

In Trial 1 of the vacuum kiln, both *C. huliohia*- and *C. lukuohia*-colonized logs were used with the kill + dry treatment schedule. The pathogens were found from 25 to 78 percent of wood samples assayed ($n = 288$) and there was no pattern to fungal recovery on the basis of sapwood depth sampled (Table 2). Neither fungus was isolated from logs after the 4.5-day kill + dry kiln schedule. In contrast, fungal detection rates for control logs held outside the kiln were 63 percent ($n = 24$ subsamples) and 25 percent ($n = 24$ subsamples) for *C. lukuohia* and *C. huliohia*, respectively (data not shown).

For the second and third trials, study logs received the more gradual kill-only schedule over 40 and 48 hours (Table 2). For the second trial, *C. huliohia*-infested logs were used, and the fungus was isolated from 31 percent of 144 subsamples (combined depths) before kiln treatment. *Ceratocystis lukuohia*-infested logs were used in the third trial and the pathogen was isolated from approximately 55% subsamples ($n = 144$, combined depth) before treatment. In these trials, more fungi were recovered from the inner sapwood zones than outer (Table 2). *Ceratocystis huliohia* was not isolated from disk subsamples in Trial 2 ($n = 120$) and *C. lukuohia* was not isolated in Trial 3 ($n = 120$) after their kiln treatments. In contrast, rates for fungal detection in the control logs held outside the kiln were 17 percent ($n = 24$ subsamples) and 29 percent ($n = 24$ subsamples) for *C.*

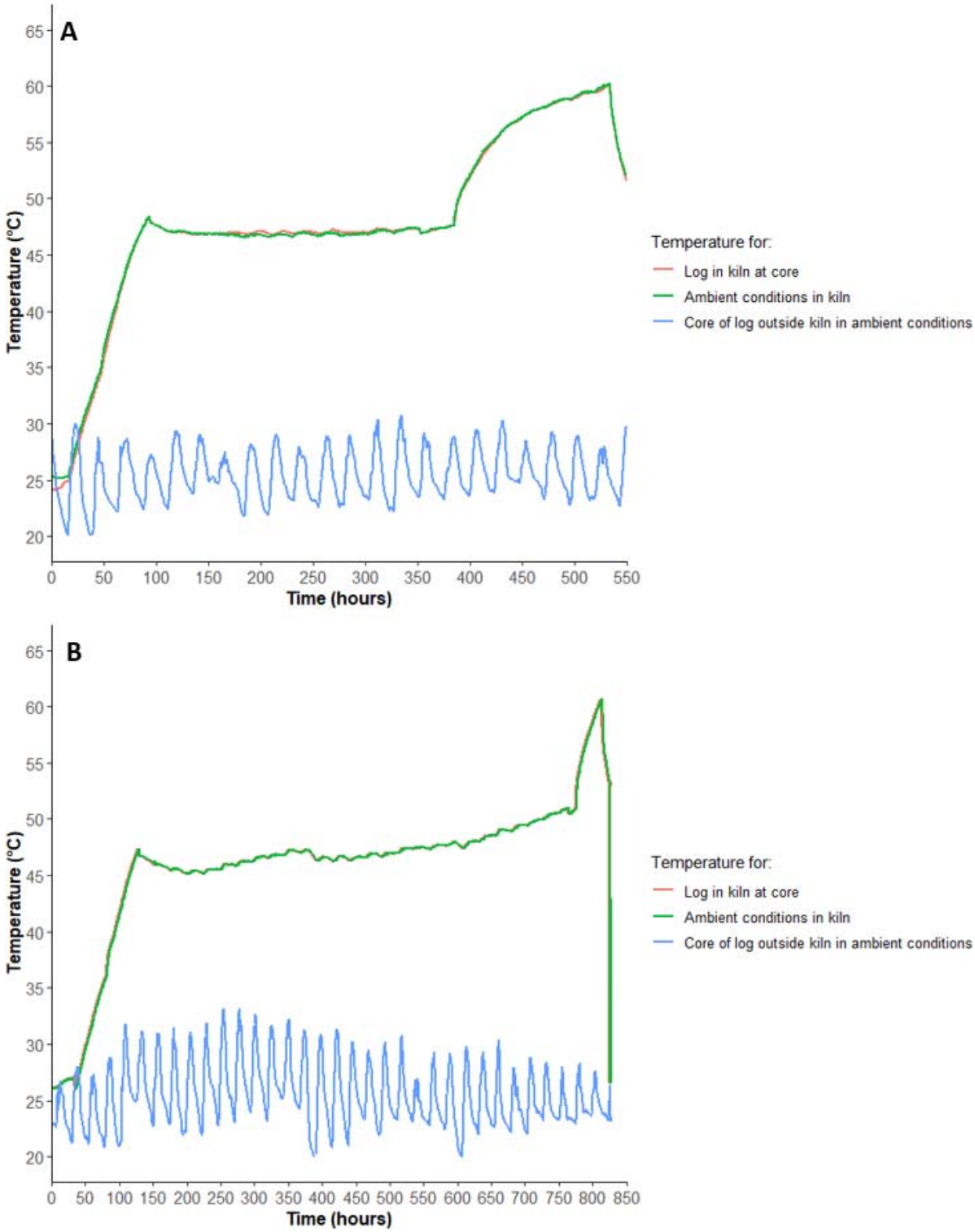

Figure 2.—Temperature profiles of a 20+-day kiln schedule followed by heat treatment of Metrosideros polymorpha *poles to 60°C using a dehumidification kiln. The first trial (A) was 22 days and the second trial (B) was a 33-day kiln run. Temperature measurements were taken at the core of logs at their mid-length and of ambient conditions inside the kiln box. Monitored logs were held inside the kiln and outside the kiln at ambient temperatures.*

huliohia and *C. lukuohia*, respectively. Thus, the vacuum kiln treatments were successful in eradicating viable pathogen propagules from the colonized logs. This threshold temperature eradicated *Ceratocystis* and several tree pathogens, including *Phytophthora cinnamomi* and *Lasiodiplodia theobromae* (Ramsfield et al. 2010; Juzwik et al. 2019b, 2021, 2022). The heating schedule of 56°C/30 min is the accepted wood treatment standard to eradicate gypsy moth (*Lymantria dispar*) and Asian longhorn beetles (*Anoplophora glabripennis*) in the United States (Myers and Bailey

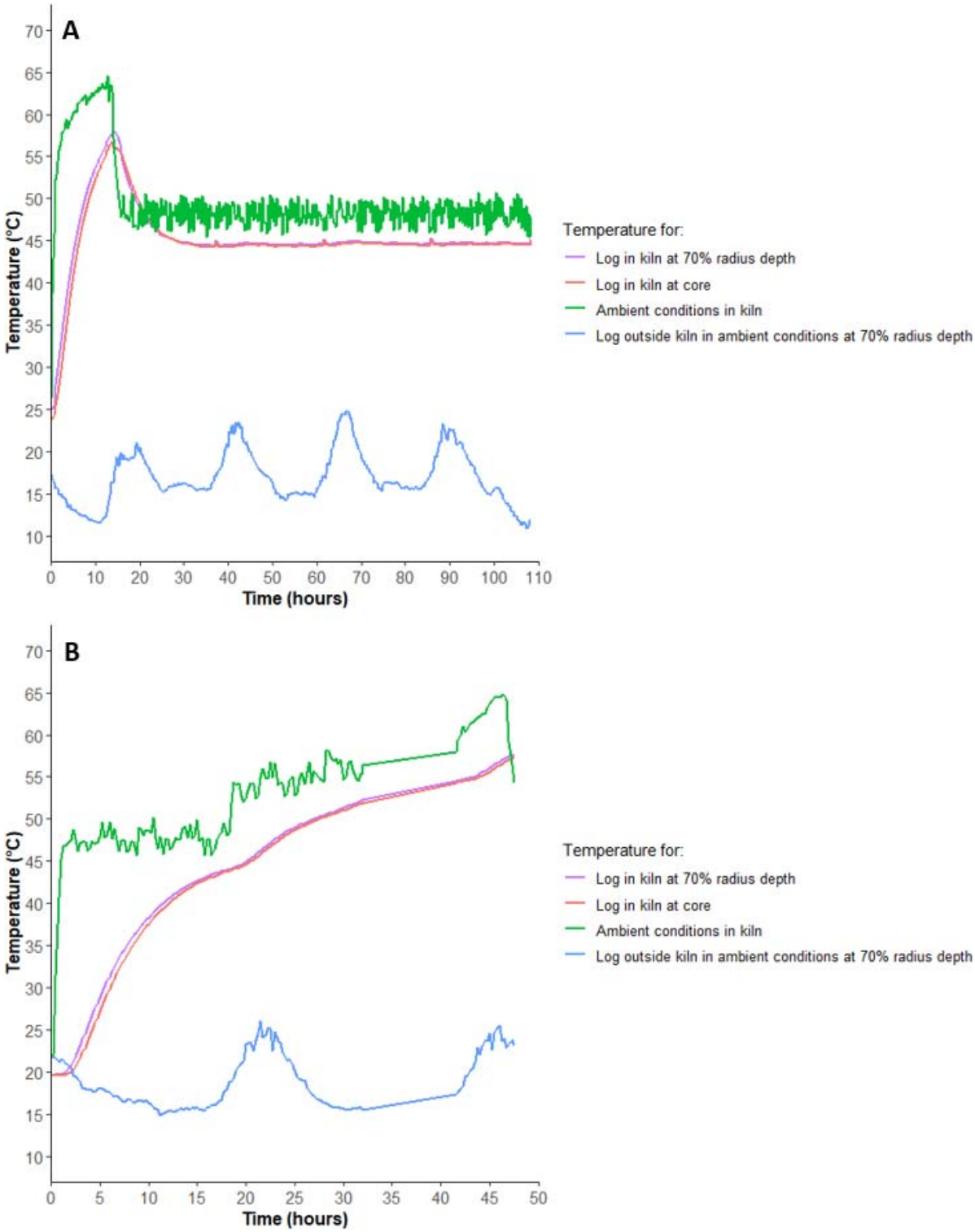

Figure 3.—Temperature profiles of kiln schedules followed by heat treatment to 56°C of Metrosideros polymorpha *logs using a vacuum kiln. Trial 1 (A) was a kill + dry schedule that attempted to optimize vacuum drying and Trial 3 (B) was a kill-only schedule that did not optimize for log drying. Temperature measurements were taken at the core, at 70 percent radius depth of logs at mid-length and of ambient conditions inside the kiln box. Monitored logs were held inside the kiln and outside the kiln at ambient temperatures.*

2011, Heat Treatment Standard T314-b, National Plant Board Firewood Guidelines 2020, USDA Treatment Manual 2022) and is the international standard for treating solid wood packing material to prevent the unintentional spread of wood inhabiting pests and pathogens (ISPM 15; International Plant Protection Convention 2006).

Within this trial, log-core temperatures were monitored at a radial depth of 70 percent to the core since neither ROD

Table 1.—Carrot-baiting recovery means for detection of rapid ʻōhiʻa death-associated fungi Ceratocystis lukuohia *and* Ceratocystis huliohia *from the outer and inner sapwood of debarked logs from artificially inoculated* Metrosideros polymorpha *trees before dehumidification kiln treatment.*

					Percent *Ceratocystis* detection on carrot baits	
Trial no.	Fungus	No. logs	Sapwood location[a]	No. locations assayed	Mean	95% CI
1	*C. huliohia*	6	Outer	48	87.50	78.05–96.95
			Inner	48	81.25	70.09–92.41
	C. lukuohia	6	Outer	48	100.00	—
			Inner	48	93.75	86.83–100.67
2	*C. huliohia*	9	Outer	72	98.61	95.89–101.33
			Inner	72	76.39	66.51–86.27
	C. lukuohia	9	Outer	72	100.00	—
			Inner	72	95.83	91.19–100.48

[a] Outer sapwood was collected from 0.5 to 2.0 cm and inner sapwood at 2.5 to 5.0 wood-disk radial depth.

Ceratocystis species colonizes the core heartwood (Hughes et al. 2020, Juzwik et al. 2019a). Although USDA log and firewood treatment schedules (T314) measure temperature to the log's core (USDA Treatment Manual 2022), in our study, wood temperatures at a 70 percent radial depth were similar to that of the core (Fig. 3) and thus increasing the target depth would likely not require extensive additional heating times.

Conclusions

The results of this study indicate that heat treatment using a dehumidification or a vacuum kiln can eradicate viable *C. lukuohia* and *C. huliohia* from infested *M. polymorpha* poles or logs. The dehumidification kiln trials heated ʻōhiʻa poles (2.1 to 2.5 m long, 8.0 cm diameter) in a 20+-day kiln schedule followed by heat treatment to 60°C for a minimum of 5 hours. Vacuum kiln trials heated logs (1.7 m long, 20 to 25 cm diameter) at 70 percent radial depth toward the core to 56°C for a minimum of 30 minutes before lowering the kiln temperature. On the basis of the above heat treatment, viable propagules of both *C. lukuohia* and *C. huliohia* were eradicated from ʻōhiʻa wood, whereas in comparison, nontreated wood contained high levels of viable *Ceratocystis*. Results of these studies provide baseline treatment schedules to safely use ʻōhiʻa wood, including the potential for salvage logging from known diseased trees. These data can also allow state regulators and mill owners to develop an operational phytosanitary standard (Wang et al. 2014) for wood destined for off-island shipment.

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Table 2.—Carrot-baiting recovery means for detection of rapid ʻōhiʻa death-associated fungi Ceratocystis lukuohia *and* Ceratocystis huliohia *from the outer and inner sapwood of debarked logs from artificially inoculated* Metrosideros polymorpha *trees before vacuum kiln treatment.*

					Percent *Ceratocystis* detection on carrot baits	
Trial no.	Fungus	No. logs	Sapwood location[a]	No. locations assayed	Mean	95% CI
1	*C. huliohia*	6	Outer	72	29.17	18.59–39.74
			Inner	72	25.00	14.93–35.07
	C. lukuohia	6	Outer	72	62.50	51.24–73.76
			Inner	72	77.78	68.11–87.45
2	*C. huliohia*	6	Outer	72	29.17	18.59–39.74
			Inner	72	33.33	22.37–44.30
3	*C. lukuohia*	6	Outer	72	43.06	31.54–31.54
			Inner	72	66.67	55.70–77.63

[a] Outer sapwood was collected from 0.5 to 2.5 cm and inner sapwood at 3.0 to 5.0 wood-disk radial depth

and does not imply its approval to the exclusion of other products or vendors that also may be suitable.

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