Exaquest Carbon

Wood drying and preservation research results for January, 2022 – present

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Overview

Trees use photosynthesis to capture CO_2 from the atmosphere and synthesize wood. When trees die, their wood is decomposed by microbes and fungi, which release the captured CO_2 back to the atmosphere. Preserving waste wood by storing it dry to prevent dry matter loss (DML; the loss of mass of components of the wood other than water) thus removes CO_2 from the atmosphere by keeping photosynthetically captured CO_2 "locked" in the form of wood. To stop DML, Exaquest Carbon has proposed that waste wood be collected and dried *in situ* within plastic containers using intermittently powered fans whose operation is compatible with solar energy availability. The containers are then sealed and stored aboveground, which maintains dry conditions and prevents DML. In the proof-of-concept experiments described herein, no measurable DML has been observed during drying or during ongoing storage and monitoring for up to 318 days. Based on these results and a review of the literature, it can be anticipated that dry wood, stored enclosed and below 71% relative humidity, can be preserved for millennia.

Scientific background

Wood resists decay for millennia when it is kept sufficiently dry and protected from environmental stressors such as sunlight, insects, and excessive moisture.[1,2,3] The latter is a key determinant in the decomposition process; freshly cut wood often has a moisture content (MC) exceeding 50% on a wet basis (i.e., when including moisture in the total weight of the wood), and fungal and microbial decay readily occur unless the wood is dried to 17%-23% MC or lower.[4,5,6] Excessive moisture also amplifies the effects of physical degradation caused by UV rays, promotes nonenzymatic depolymerization in wet or waterlogged wood, and renders wood on land habitable to pests such as beetles and termites.[2,3,7,8]

Wood decomposition virtually stops under highly desiccating conditions, based on millennia-old dead wood found preserved at high altitudes.[9] In archaeology, dry wood that is protected from moisture has been preserved for several millennia, with only minor chemical and morphological changes evident upon microscopic examination.[1,10] It can thus be anticipated that wood, dried to 17% MC or lower and protected from the elements, will not measurably decompose biologically, physically, or chemically, and that the carbon captured in the wood will remain there for millennia.

The process by which microbes and fungi decompose wood proceeds most efficiently over a relatively narrow range of conditions. The overwhelming majority of microbes function optimally when the water activity (WA) is between 0.95 and 1.00[11,12,13,14] and temperature is between 5 °C and 43 °C (41-109 °F).[12] The WA is functionally equivalent to the relative humidity (RH), where WA = RH/100, and is a proxy for the fraction of water that is biologically available. Dead wood decomposes very slowly outside of these limits and, as discussed below, dry wood at equilibrium with air having a RH below 71% is in a biologically stable state resistant to decomposition.[15,16,17]

If sufficient moisture is present, wood can decay into CO_2 and water under aerobic conditions, and into methane under anaerobic conditions. In temperate environments the aerobic decay process for wood is driven primarily by the growth of fungi and molds and—to a lesser extent—bacteria, which tend to colonize wood in aquatic environments or buried in saturated soils.[18] Most wood decay fungi are hydrophilic, require WA > 0.97 to function, and grow optimally at a wood MC above the fiber saturation point (FSP) but below full saturation.[19,20] The FSP is the MC at which the pores and microstructure of wood become filled with excess water that is then easily accessed by microorganisms. The FSP varies among wood species and can fall between 17% and 23% MC, which is achieved at a RH of 88-100%.[4,5,6] It is thus expected that wood decay in air below a RH of ~88% will be very slow and will produce CO_2 and water as opposed to methane. As discussed below, wood is not expected to decay biologically at RH < 71%.

Nearly all molds and fungi (the primary organisms responsible for aerobic decay of wood) require RH > 75% to grow.[21,22,23] The lower limit on WA for most mold growth is 0.80 (RH = 80%), although a few known molds can grow at WA as low as 0.75.[6,20] Bacterial growth generally requires a MC above the FSP and wood must usually have a MC > 50% to be attacked by bacteria.[19] The lower limit on WA for most bacteria is 0.98 (RH = 98%), although some halophilic strains can survive at lower WA in saline environments.[6] There are very few reports of microbial growth of any kind on any substrate below WA = 0.71.[24] A handful of microorganisms have been found to grow *in vitro* at WA as low as 0.605 in the presence of certain solutes, but to our knowledge, such growth has not been observed on dry wood. Fungi isolated from decaying wood were not observed to grow *in vitro* below WA = 0.71,[1] and even so-called "dry-rot" fungi, which can digest wood with a MC below the FSP, require the ability to draw from a nearby water source, often the soil.[6,20,25] It is generally accepted that the lower limit for cell division for any microorganism is WA = 0.605,[6,13] and that DNA itself denatures and cannot be transcribed below WA = 0.55.[12,26] Allowing for some limited fungal growth down to WA = 0.71, dry wood preserved below RH 71% will not decay by biological routes.

In addition to biological attack, UV light and wet-dry cycling break down exposed wood over time. Photodegradation from UV light is the most damaging of these stressors.[27] However, UV light penetrates at most 75 microns (0.075 mm) into the wood surface,[28] and only 5-15 mm is lost from the surface per 100 years for wood that is isolated from the ground but is otherwise exposed to the elements.[7] Consistent with expectations from the microbiology and wood aging literature, intact wooden artifacts obtained from the Egyptian Pyramids—located in a desert with an average annual RH of 43%—have been found to be over 4,000 years old using radiocarbon dating.[10] The ages of dry and well-preserved dead wood and charred logs—archaeological specimens taken from excavations in the Sonoran desert in the southwestern United States, which has an average annual RH of 33%—have also been dated up to 1,800 years old.[7]

In summary, wood decay fungi and bacteria cannot function or reproduce below a WA of about 0.71 (RH = 71%) because the biologically available water under these conditions is insufficient to sustain growth and metabolism.[13,20,29,30,31] The equilibrium MC of wood at 71% RH is 11-12%,[5] well below the FSP of 17-23% required for fungal growth, and well below the minimum for virtually all bacterial growth. Wood that is dried to its equilibrium MC and stored below 71% RH can be preserved indefinitely, thereby removing the carbon captured in the wood from the global carbon cycle and preventing its re-release to the atmosphere. Notably, more than half the land area in the United States has an average annual RH below 71%.

Methods

Experiments to date have been centered on investigating the drying of wood (in the form of chips, chunks, or small logs) with forced ambient air, and on the stability of the dried wood when stored within sealed plastic containers. Plastic containers were purchased and were then equipped with fans for drying fresh wood *in situ* using ambient air (RH < 60%). The typical starting MC of the wood was > 30-40% and the equilibrium MC of the dried wood was < 10%, well below the threshold for fungal and bacterial growth.

Three experiments are currently ongoing as of this writing; drying or long-term storage and monitoring are in process for all experiments. The waste wood employed has included fresh chips and chunks from hardwoods (e.g., oak) and softwoods (e.g., Ponderosa pine), and chips of mixed origin obtained from local recycling facilities. The oak and Ponderosa pine were sourced, respectively, from tree service operations and forest management activities. The wood for each experiment was placed within 55-gallon plastic drums or a 550-gallon plastic water tank. Details for each experiment are given in Table 1.

***Table 1**. Description of waste wood, containers, fan power draw, and duration of monitoring and storage to date for the three experiments.*

Experiment number	Wood type	Wood origin	Container	Fan power (W)	Location of experiment	Duration (days)
1	Oak chips	Tree service work	55-gallon plastic storage drums	85	Alameda, CA (indoors)	79-283
2	Oak chunks & mixed wood chips	Tree service work & recycling facility	55-gallon plastic storage drums	85	Alameda, CA (indoors)	70-274
3	Ponderosa pine chips	Defensible space clearing activities	550-gallon plastic water storage tank	53	Nevada City, CA (outdoors)	318

Using the low-power fans, ambient air having an average RH < 60% was forced through the wood[32,33] within the containers. The air was injected through or near the bottom of each container to allow the pressurized air to migrate through the mass of wood and exit at the top of each container. Airflow was continued until the wood had reached equilibrium with the ambient air—inferred from convergence of the RH within the containers to ambient RH, and on stabilization of the container weight, which decreases during drying due to water evaporation. Airflow also has the benefit of preventing the anaerobic conditions that promote methane formation.

Intermittent and constant fan schedules were employed to simulate drying using both a constant power source and an intermittent source such as solar panels with minimal battery backup. After drying was completed, the fans were shut off and the containers capped. Conditions in the containers are currently being monitored using Bluetooth-enabled sensors. Moisture content measurements were performed before and after drying using the oven-dry method,[34] and were combined with measurements of the initial and final wood weight to deconvolute mass losses from water evaporation and dry matter loss (DML; the loss of mass of components of the wood other than water), if any. To monitor for possible DML during ongoing storage, the containers continue to be weighed regularly to check for mass loss, and the RH and temperature monitored for increases associated with fungal or microbial respiration.

In practice, moisture reuptake in dried wood can occur from exposure to precipitation, slow adsorption of water from an increase in ambient humidity, capillary penetration of water into wood in contact with the ground or in the presence of condensation, water transport by certain fungi, and water formed during fungal or microbial respiration.[6] The plastic storage containers are therefore watertight, remain closed after drying, and are stored aboveground properly distanced from soil. In the unlikely event of water intrusion, forced ambient air can be re-applied using the fans to return the wood to a dry state.

Results

Summary

The experimental results to date demonstrate that:

1) Wood can be fan-dried with ambient air, without measurable decomposition, using a low and intermittent power draw (< 100 W), which facilitates the use of solar panels to power the fans.
2) Dry matter loss (DML; the loss of mass to decomposition) has not been detected during drying or storage and ongoing monitoring for up to 318 days. Observed mass loss has been attributable thus far to water loss during drying.
3) Relative humidity, and thus the MC of the dry wood within the closed containers, does not fluctuate appreciably in response to changes in ambient RH, and can therefore be maintained relatively passively. This observation implies that dried wood can be maintained below the decay threshold of 71% RH so long as the average ambient RH remains below this level. Excursions to higher RH will have little impact on RH within the closed storage containers.

Data for experiment 1

Experiment 1 was started on April 4, 2022. Two 55-gallon plastic drums were charged with fresh oak wood chips, obtained from tree service work performed in Oakland, CA. The fan was operated constantly for drum 1 until the wood had dried to equilibrium MC. For drum 2, the fan was operated intermittently. Cumulatively, the fan for drum 2 was run for 37% of the total drying period of 36 days, while the fan for drum 1 was operated constantly during a total drying period of 23 days.

Key results for experiment 1 are summarized in Table 2 and plots of the RH, temperature and wood weight versus time are given in Figures 1a and 1b for drum 1 and Figures 2a and 2b for drum 2. To monitor conditions within the drums, sensors were located at 1/3rd and 2/3rd of the height of the chips in each drum, on top of the chips (i.e., at the airflow effluent), and on the floor of the room to monitor ambient conditions.

The sensors located at the effluent and at 2/3rd the height of the chips were removed for other experiments after 76 days for drum 1, and all of the sensors were removed from drum 2 for other uses after 71 days; for this reason, data for the removed sensors do not extend over the full time durations in Figures 1 and 2. Drum 2 was emptied and the experiment concluded after 79 days, to allow for use of the drum elsewhere. The temperature and RH for Drum 1 continue to be monitored continuously, and the drum continues to be weighed roughly once per week.

Table 2. *Summary of key results for experiment 1.*

Drum	Fan operation	Duration (days)	Drying time (days)	Fan energy (kWh/kg H_2O)	Initial/Final MC (%)	Dry matter loss (%)
1	Constant	283 (ongoing)	23	3.5	44/8	None detected
2	Intermittent	79 (ended)	36	1.3	44/8	None detected

The initial and equilibrium MCs of each drum were, respectively, 44% and 8%. No measurable DML has occurred during drying or storage of either drum; based on weight and MC measurements, all mass loss thus far has been attributable to water loss during drying. The fan energy consumption was 63% lower for the intermittently operated fan used with drum 2, versus the constantly operated fan used with drum 1, while drying time was considerably longer for drum 2 (36 days) vs for drum 1 (23 days). Because no DML was observed, the intermittently operated fan schedule is preferred because of its compatibility with an intermittently available power source such as solar energy.

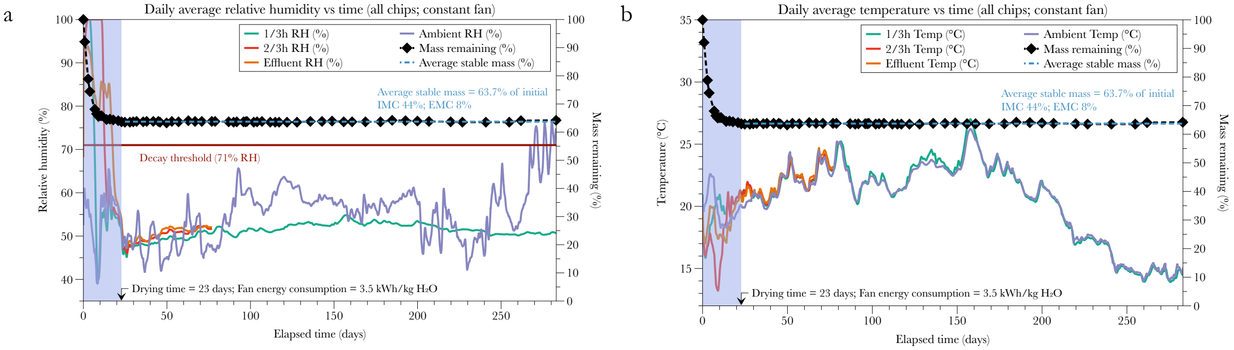

Figure 1. *Plots of (a) relative humidity, (b) temperature, and percentage of wood weight remaining vs time for drum 1 of experiment 1.*

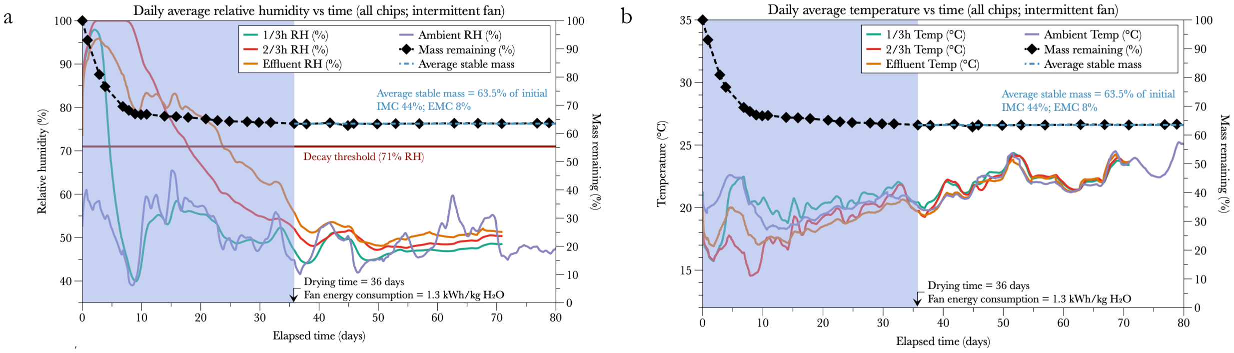

Figure 2. *Plots of (a) relative humidity, (b) temperature, and percentage of wood weight remaining vs time for drum 2 of experiment 1.*

Data for experiment 2

Experiment 2 was started on April 13, 2022. Two 55-gallon plastic drums were charged with a mixture of 57-60% w/w fresh oak wood chunks, obtained from tree service work performed in Oakland, CA, and 40-43% w/w mixed wood chips obtained from a recycling facility in San Francisco, CA. The fan was operated constantly for drum 1 until the wood had dried to equilibrium MC. For drum 2, the fan was operated intermittently. Cumulatively, the fan for drum 2 was run for 48% of the total drying period of 48 days while the fan for drum 1 was operated constantly during a drying period of the same length (i.e., 48 days). The similarity in drying times for the two drums (despite the fan being powered on for different percentages of the drying period for each drum), indicates that the drying was likely diffusion-limited.

Key results for experiment 2 are summarized in Table 3 and plots of the RH, temperature and wood weight versus time are given in Figures 3a and 3b for drum 1 and Figures 4a and 4b for drum 2. To monitor conditions within the drums, sensors were located at the center of the chips in each drum, on top of the chips (i.e., at the airflow effluent), and on the floor of the room to monitor ambient conditions.

Table 3*. Summary of key results for experiment 2.*

Drum	**Fan operation**	**Duration (days)**	**Drying time (days)**	**Fan energy (kWh/kg H_2O)**	**Initial/Final MC (%)**	**Dry matter loss (%)**
1	Constant	274 (ongoing)	48	6.2	41/9	None detected
2	Intermittent	70 (ended)	48	3.0	42/9	None detected

The sensor at the effluent was removed for use in other experiments after 56 days for drum 1, and both sensors were removed from drum 2 for use elsewhere after 56 days; data for the removed sensors do not extend over the full duration of the experiments in Figures 3 and 4. Drum 2 was emptied and the experiment concluded after 70 days, to allow for use of the drum elsewhere. The temperature and RH for Drum 1 continue to be monitored continuously and the drum continues to be weighed roughly once per week.

The initial and final MC of the wood in each drum were, respectively, 41-42% and 9%. No measurable DML has occurred during drying or storage of either drum; based on weight and MC measurements, all mass loss thus far has been attributable to water loss during drying. The fan energy consumption was 52% lower for the intermittently operated fan used with drum 2, versus the constantly operated fan used with drum 1, while drying time was 48 days for both drums. This observation suggests that the drying was diffusion-limited in both drums. Because no decomposition was observed during or after drying, the intermittently operated fan schedule is preferred because of both energy savings and compatibility with intermittently available solar energy.

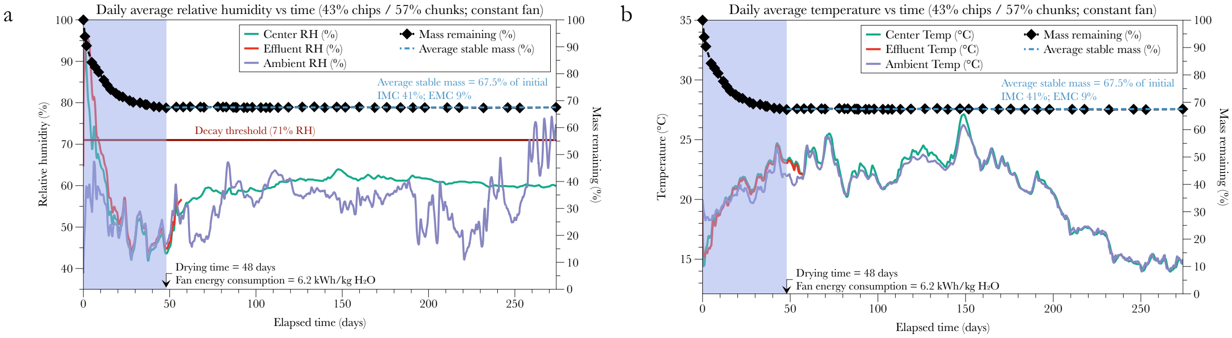

***Figure 3**. Plots of (a) relative humidity, (b) temperature, and percentage of wood weight remaining vs time for drum 1 of experiment 2.*

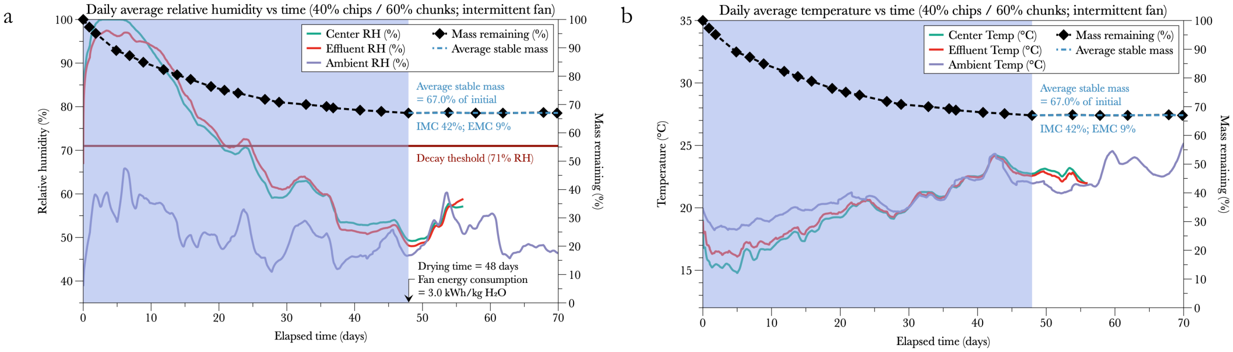

***Figure 4**. Plots of (a) relative humidity, (b) temperature, and percentage of wood weight remaining vs time for drum 2 of experiment 2.*

Data for experiment 3

Plots of the RH, temperature, and wood weight versus time for experiment 3 are given in Figures 5a and 5b. Experiment 3 was started on Jan 22, 2022. A 550-gallon plastic water storage tank was charged with Ponderosa pine chips, obtained from defensible space clearing in Nevada City, CA, that were field-dried to 25% MC prior to being loaded into the tank. The fan was operated intermittently for 71 days until the wood had dried to approximately equilibrium MC. To monitor conditions within the tank, 4 sensors were located within the chips in the tank, and 2 sensors were located at the inlet to the fan (to monitor ambient conditions) and on top of the chips within the tank (i.e., at the air effluent). The tank RH and temperature presented in Figures 5a and 5b are averages of the 4 measurements obtained from the sensors placed within the mass of chips.

Key results for experiment 3 are summarized in Table 4. The final MC of the wood chips will be measured upon completion of the experiment and emptying of the tank, in order to deconvolute the total observed mass loss into components from water loss from drying, and from DML (if any). However, it can be inferred that no measurable DML has occurred since drying, based on a constant weight of the wood chips since the fan was turned off on day 71. The tank RH and temperature continue to be monitored continuously and the tank continues to be weighed periodically.

***Table 4**. Summary of key results for experiment 3.*

Fan operation	Duration (days)	Drying time (days)	Fan energy (kWh/kg H_2O)	Initial/Final MC (%)	Dry matter loss (%)
Intermittent	318 (ongoing)	71	0.28	25/TBD	TBD

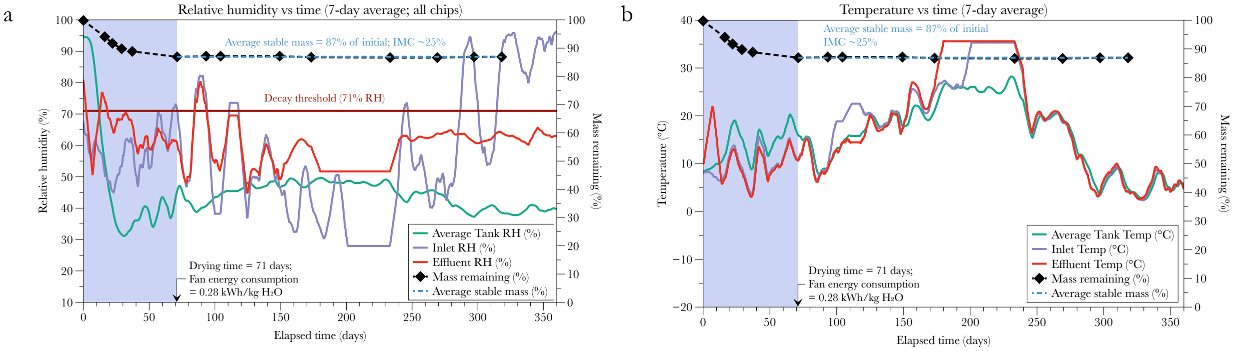

***Figure 5**. Plots of (a) relative humidity (RH), (b) temperature, and percentage of wood weight remaining versus time for experiment 3. Horizontal lines on the plots of RH and temperature correspond to lapses in data collection due to loss of battery power to sensors because of site accessibility issues. Weight measurements do not extend the full duration of the sensor measurements because ice and snow had accumulated on the outside of the tank after day 318, interfering with the accuracy of the weight measurements.*

Conclusions

It has been demonstrated that fresh wood can be dried *in situ* within storage containers using intermittently powered fans that force ambient air through the mass of wood. The fans operate effectively when operated intermittently versus constantly, which is advantageous for the drying operation, which will be powered by solar panels in practice. Dry matter loss (DML; the loss of mass of components of the wood other than water) has thus far not been observed during the drying period or subsequently during storage at an average relative humidity < 60% over a period of up to 318 days, consistent with expectations from the microbiology and wood aging literature. Conditions within the closed containers are not readily disturbed by fluctuations in external ambient conditions after drying has been completed, and can thus be maintained relatively passively.

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