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Capturing Heat from a Batch Biochar Production System for Use in Greenhouses and Hoop Houses

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Abstract: Biochar is charcoal produced at comparatively high temperature and used as an agricultural amendment, which also sequesters carbon. Most of the research on biochar manufacture in the United States has either focused on large-scale continuous systems with multiple products or small batch systems with biochar as the only product. At James Madison University in Harrisonburg, Virginia, we have worked on a batch system to make high quality biochar while capturing the heat for use either as a backup system for hot water heating, or to heat a greenhouse in winter. The system is now in its third iteration. In the first, we used a small intramural grant to experiment with low cost material using a minimalist design. While the unit captured some heat, operation of the design was smoky and hazardous to handle. The second design, funded by a larger intramural research grant, captured considerable heat, made 8-10 kg of biochar per burn and captured up to 250 MJ per batch of biochar made, but remained smoky. The third generation pyrolysis unit was constructed on Avalon Acres Farm in Broadway, Virginia, funded by a 25 × 25 grant through James Madison University (JMU). This unit makes the same amount of biochar, with less smoke, and sends the captured heat to a storage tank to help heat a greenhouse and home on the site. Our average efficiency of heat transfer is 12.5% of the total heat value of the starting woody biomass, a number we believe can at least double.

Key words: Biochar, production, heat capture, greenhouse, hoop house.

1. Introduction

Biochar, charcoal used as an agricultural amendment that sequesters carbon, is becoming more widely known around the world, as noted in Albert Bates' the biochar solution [1] and Paul Taylor's the biochar revolution [2]. The number of people working on biochar has expanded greatly in the last decade, as has the range of activities [3]. This article chronicles one team's effort to produce, characterize and use biochar on small farms in the Shenandoah Valley of Virginia.

The headwaters of the two branches of the Shenandoah River are located in Augusta and Rockingham counties, the Southern area of the Shenandoah watershed. It is the leading agricultural area in Virginia, with a heavy emphasis on poultry production, cattle grazing, and some commodity crops like corn and soybeans. A growing minority of agricultural production in the valley occurs on small-scale organic or "natural" farms, some tied to generations of farming families, others stimulated by the success of Polyface Farm and the writings of Joel Salatin, and still other newcomers influenced by the permaculture movement and community supported agriculture. It is this collection of farmers that this project assists.

The dominant farm type in the Shenandoah Valley is relatively large, 250 acres or more, chemical and mechanically dependent, and run by one or two farmers with an average age of 58 years. These farmers often supplement their incomes with off-farm jobs. The new small farmers are quite a bit younger, have much smaller acreage and focus on vegetable crops, some fruits, and rapid rotational grazing. Their income is largely dependent on selling high value seasonal

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crops like salad greens, onions, tomatoes, peppers, squash (summer and hard varieties), sweet corn, herbs and more. Many of these new small farmers want to extend the season on a lot of their crops, especially salad greens and tomatoes. The technology of choice for season extension is the high tunnel or hoop house coated with UV resistant plastic sheeting.

Hoop houses vary in size between 24 feet wide and 50 feet long to 30 feet wide and 100 feet long. They enable farmers to grow crops into November, about a month after the first frost in this region, and start again in early March, well before the last frosts, which historically occur in early May.

Our team's idea is to extend this season even further using the production of biochar as the source of heat. The heat produced is captured in the thermal mass of the production unit, called a retort, and slowly released inside the hoop house at night, keeping away the frost. In the morning, biochar contained in the pyrolysis unit can be removed and the biochar then prepared for use as an amendment on the farm.

2. Design of the Biochar Retort and Initial Trials

2.1 Initial Design and Analysis of the Biochar Unit

The research was begun working with the production of biochar and designing low-cost, locally adapted pyrolysis chambers in 2009. For 3 years, I have overseen student research projects' focusing on re-designs suited for particular locales, as well as the construction and implementation of these units. The initial design my students and I selected involved a modified version of a common barrel retort [4]. The barrel has a lid with a clamp closure to lock out most air. At the opposite end of the barrel we welded a two inch pipe to the back, then using two elbows brought the pipe under the barrel and drilled a series of holes in the pipe. We then mounted the barrel about one foot off the ground on a stand so that a fire could be built underneath (Fig. 1). In order to keep the fire focused on the barrel, we built a dry lay firebrick wall around

Fig. 1 Picture of the orginal pyrolysis chamber built in 2010.

three sides and capped it with a metal lid. The door for the retort was simply a metal sheet with a welded handle. It was crude but effective, and much lower cost than other models.

In order to keep track of temperatures, we used a 4-channel data logger with 3 high temperature K-type thermocouples. One of the thermocouples was threaded inside a hole in the side of the barrel to keep track of interior temperature; the second thermocouple was attached to the outside of the barrel; the third thermocouple kept track of temperature in the fire chamber. We then ran a series of tests to see how the temperature profiles looked, aiming for an ideal interior pyrolysis temperature of 450 °C to 550 °C, as suggested in the work of Lehmann [5].

While this design produced good biochar, it did not prove well suited to capturing heat for a greenhouse. We attempted to fix this by running water through a copper pipe laid on the metal plate serving as a lid for the burn chamber, but this was not a satisfactory option. The metal plate was badly warped by the repeated heating during the burns and did not hold heat inside a satisfactory way either. The same was true for the door of the burn chamber. At this point, we decided major changes in order for the design.

2.2 Redesign of the System and Further Testing

The first major change was recognition that a hoop house would require greater heat capture and less smoke loss to be effective. We decided to go with a metal-framed system, with inlaid, dry lay fire brick and a hinged and latched brick insulated door [6]. On top of the metal frame, we designed a 500 L soft steel tank that sat snugly on the frame with rock wool insulation closing any gaps (Fig. 2). At first, we used the same barrel system for the pyrolysis chamber inside this burn chamber, but we recognized that a standard barrel was too small, and the distance between the gas pipe and the barrel was also too small for effective use. Then, we had a barrel made with a volume of 215 L and the gas pipe mounted 15 cm below the barrel (Fig. 3). The barrel is 100 cm long and is 52.3 cm in diameter.

Burns completed with this system in the winter of 2010-2011 showed good promise. Again, we monitored the temperature of the burns using a four-channel data logger, this time with the three K-type thermocouples in the same position as before, with a fourth J-type lower temperature thermocouple placed in the roof mounted water tank to keep track of temperatures. A sample of one burn's temperature data is shown in Fig. 4.

The intent was to use the least amount of wood possible for combustion, adding only enough to achieve pyrolysis. Sometimes this led to uneven and slow heating of the pyrolysis chamber. A number of different types of woods were placed in the pyrolysis chamber at different times. Table 1 gives a summary of the burn data from five different materials pyrolyzed, along with their weights before and after burns, and the amount of wood used for fuel to get pyrolysis started.

As Table 1 shows, the yield of biochar as a percentage of the original feedstock is variable. This is in large part dependent on the moisture content of the feedstock and the firewood used to heat the pyrolysis chamber. We found that if you start with dry wood, the amount of wood pyrolyzed and the amount of fuel needed to drive the process are approximately equal as long as you are above about 20 kg for each. Completely filling the pyrolysis chamber works, as seen in burn 7, but the process brought the water in the 500 L tank to a boil causing a loss of water through the two inch pipe in the top of the tank used to fill it with water and act as a pressure release point. This also exceeds the ability of the thermal mass to capture heat, a sign that we have not calculated the size of the tank correctly.

Fig. 2 Exterior of the redesigned pyrolysis unit, the barrel in Fig. 3 is inserted though the door.

Fig. 3 A 215 L barrel with bolted lid and gas pipe.

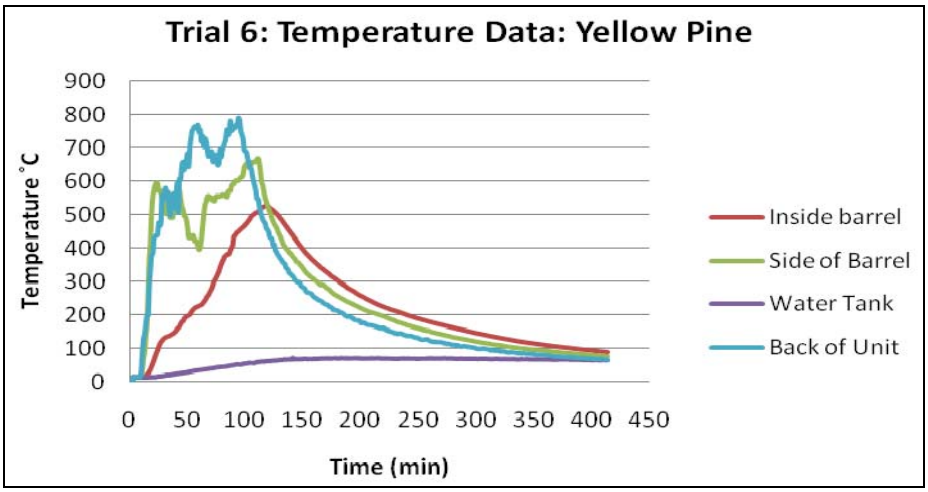

Fig. 4 Burn 6 temperature data-yellow pine. Side is the pyrolysis chamber, barrel is inside the chamber, back is at the chimney exit and tank is the water tank [6].

Table 1 Data collected during the 2010-2011 period. These burns were conducted using the system depicted in Fig. 1.

	Burn date	Wood type	Pyrolized wood, starting kilogram	Biochar produced kilogram	Biochar	Wood used for fuel kilogram	Highest production temperature[1]
1	Jan. 29, 2011	Yellow pine	20.41	6.35	31%	NA	560 °C
2	Feb. 5, 2011	Black walnut	24.33	NA	NA	40.9	430 °C
3	Feb. 12, 2011	Miscanthus	7.36	2.4	33%	30.83	465 °C
4	Feb. 13, 2011	Red cedar	12.16	4.5	37%	25.9	460 °C
5	Feb. 19, 2011	Bamboo	11.9	3.75	32%	29.85	480 °C
6	Mar. 19, 2011	Yellow pine	34.8	7.9	23%	37.65	520 °C
7	Mar. 26, 2011	Yellow pine	54.5	12.7	23%	46.5	520 °C

[1]Highest temperature reached inside the barrel during the burn.

Table 2 shows the maximum amount of energy captured in the water of the tank at its highest temperature and the amount this represents in relation to the total energy in the original wood. Though this amount of energy captured by the water has value, it does not represent the total energy capture. A substantial amount of energy is captured by the 1,000 kg of firebrick, with a specific heat of 0.2 calories per gram °C. In addition, considerable energy is given off to the environment that would warm the hoop house if it was inside. Even so, we estimate that one-third to one-half the energy is lost through the chimney and not available to warm a hoop house.

A number of additional lessons were learned from this series of burns. First, dry laid firebrick is insufficient to eliminate smoke loss from the sides of the burn chamber. In our next iteration we used refractory mortar to reduce this problem. Second, wood size and placement in the pyrolysis chamber makes a big difference. We found that anything over 5 cm in diameter failed to completely pyrolyze, as did

Table 2 Maximum energy captured by the water tank.

Burn #	Total wood (kg^{-1})	Total wood energy (MJ^2)	Tank temperature start (°C)	Tank temperature end (°C)	Total energy capture (MJ)	Energy capture (%)
2	65.23	832	6.7	42.5	74.9	9.0
3	38.19	487	2.0	31.6	61.9	12.7
4	38.02	485	13.2	39.4	54.8	11.3
5	41.75	532	13.9	44.7	64.4	12.1
6	72.45	956	13.6	70.3	119	12.4
7	101.0	1,330	11.5	90.3	165	12.4

[1]Burns 6 and 7 used yellow pine exclusively. Burns 2-5 used a mix of woods for fuel and the material for pyrolysis is found in Table 1 above;

[2]Estimated water content for most wood is 15%. This amount was subtracted from the wood weight before doing the calculation. For yellow pine we experimentally determined the kiln-dried moisture content at 12%.

wood that was stacked too tightly in the chamber. This proved the main problem in burn 2 with black walnut. The incomplete pyrolysis was partially due to the large size of the pieces. Wood is a good self-insulator, conducting heat only slowly to its interior. Finally we needed to pay more attention to the chimney mount in the back of the retort as our ad hoc design solutions did not stabilize the chimney well.

2.3 Design and Implementation of the Avalon Acres Farm Production Unit

The next stage took us from the experimental design work to a detailed on-farm trial. This was done at Avalon Acres Farm, a 17-acre biodynamic farm near Broadway, VA, along a creek. The owners have an old farmhouse to which they added a greenhouse and workroom to process farm products. The greenhouse and workroom are partially heated using an in-floor hot water system with the hot water coming from solar panels mounted on the South facing roof, just above the greenhouse glass. Water heated by the panels is stored in a 450 gallon insulated tank in the cellar. The panels are a back-drain type, meaning that when not heated by the sun above the temperature of the stored water in the tank, they drain all their water back into the tank. The floor is heated by running water through two lengths of coiled copper pipe placed inside the tank, then circulated through the floor and back to the tank.

The design we chose for the biochar unit was simple in concept but tricky in application; the existing biochar production system was redesigned to function as a backup water-heating unit for the greenhouse [7]. The unit was built outside the cellar on the North side of the house. The water tank topping the unit was downsized to 125 L. Two nipples were welded into the tank to allow us to attach send and return pipes for the hot water going to the basement. A pump was attached to the send pipe, which then sent the heated water to two sets of tightly wound coiled copper pipes placed inside the coiled copper used to heat water for the greenhouse. The return pipe then brings lower temperature water back to the pyrolysis unit for further heating.

Three other improvements were built into the biochar production unit seen in Fig. 5. All fire brick were fitted and mortared. The unit door had a stronger hinge and a double latch for a tighter fit to the frame. Finally the chimney had an insert mounted in the back wall of the burn chamber for more stability and less smoke loss. Though it took some time to get the system working smoothly, it did transfer heat to the greenhouse and the owners were pleased.

Fig. 6 shows the graph of a burn done on March 13, 2012. Because a thermocouple failed, data from only three were recorded. The abrupt rise of the outer chamber temperature indicates that the thermocouple was pinched between two pieces of wood and did not record correct temperatures until it burned free. In this burn we used 51.5 kg of wood to start pyrolysis, more than necessary for a successful burn, and had 24.2 kg in the pyrolysis chamber, of which 5.4 kg remained at the completion of the burn. Note that the water temperature line flattens at approximately 70.0 °C, indicating a steady transfer of energy from the burn chamber tank to the interior tank. We calculated a total heat transfer of 118 MJ to the interior tank, or 14.7% of the total energy released by the wood, using 15.0 MJ/kg as our baseline wood energy value. Some of the wood energy remains in the form of biochar and is not released. We think this heat transfer value can be improved by properly insulating the system.

Table 3 shows data collected from eight of the burns conducted at Avalon Acres Farm. In this study the students were less careful about the amount of wood used to drive the pyrolysis process and as a result, temperatures commonly exceeded the 550 °C target we selected from work by Lehmann and et al. [5]. As a result, the amount of biochar made as a percentage of the orginal wet weight of the material is lower than the average for the previous year.

Fig. 5 On the left is the production unit with the heavy piano hinged door open to show the firebrick insulation and the pyrolysis barrel inside. Note also the 12 cm high water tank that makes up the roof of the burn chamber. On the right is the back of the unit next to the house where the send and return pipes are seen. These are protected from the heat with reflective aluminum insulating tape.

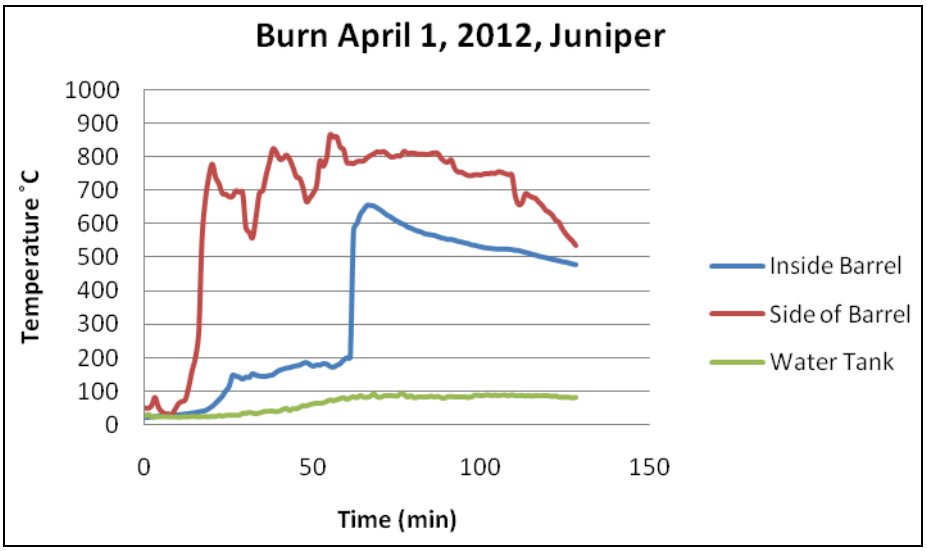

Fig. 6 Temperature data from the March 13, 2012 burn [7]. Note the highest inner chamber temperature is well above the range recommended by Lehmann et al. [3].

Table 3 Burn data from Avalon Acres Farm. These burns were conducted using the system pictured in Fig. 5.

	Burn date	Pyrolyzed wood[2], starting (kg)	Biochar produced (kg)	Biochar production	Wood used for fuel (kg)	Highest temperature[1]
1	Jan. 14, 2012	31.72	5.62	18%	47.49	NA
2	Jan. 24, 2012	31.43	8.17	26%	51.6	840 °C
3	Feb. 25, 2012	22.08	5.84	26%	78.34	NA
4	Feb. 28, 2012	15.97	4.17	26%	59.06	710 °C
5	Mar. 13, 2012	24.16	5.41	22%	51.46	670 °C
6	Mar. 18, 2012	21.64	4.28	20%	43.36	NA
7	Mar. 27, 2012	19.21	4.42	23%	60.24	690 °C
8	Apr. 1, 2012	18.39	4.28	23%	42.47	650 °C

[1]Highest temperature reached inside the barrel during the burn.

[2]The wood was a mix of locally available species, primarily American sycamore, eastern red cedar and northern red oak.

Avalon Acres Farm took the biochar produced and ground it into pieces that look about the size of large grains of sand or tiny pebbles (Fig. 7). The grinding was accomplished with a garden shredder used to prepare leaves for the compost pile. The ground biochar was then wetted thoroughly and mixed with compost made from garden waste and some sheep and chicken manure before application to garden beds. Compost has been the primary agricultural input on the farm since it began. Generally the mix was 5 shovels of compost with one shovel of biochar, but the exact amount added to each of the raised beds was not quantified.

Some of the raised beds at Avalon Acres are pictured in Fig. 8 below. The owners were particularly enthusiastic about the impact of biochar on lettuce production. They invest a lot of energy and water into the growth and preparation of their lettuce mix, sold at the Harrisonburg Farmer's Market, and they even wash each leaf by hand. Normally a bed of lettuce produces leaves for six weeks, then begins to bolt and the leaves get bitter. This year, they noticed that the leaves did not get bitter and kept picking. The bed produced for 10 weeks and the quality stayed high. The picture in Fig. 8 is a new bed that just produced its first leaves for harvest for the July 7, 2012 market. Also pictured in Fig. 8 is a bed of Swiss chard in a biochar enriched soil. Both beds received the biochar compost mixture. It is too early to tell whether production quantity or quality of the chard is affected by biochar.

Fig. 7 On the left is Eastern red cedar biochar and on the right is the ground up biochar before mixing with manure and compost.

Fig. 8 On the left is a new lettuce bed enhanced with a biochar and compost mix. On the right is a bed of Swiss chard also using the biochar compost mix.

At this point the Avalon Acres experience with biochar is anecdotal. There was no side by side comparison of beds, nor any replication. However, their experience so far with both the heat capture and use of the biochar has made them enthusiastic about prospects for the coming year. They want to increase the amount of biochar compost they apply to their crops.

3. Characterization of Biochar Produced

As biochar was made, samples of each type were kept for analysis. Jillian Becker did much of this work [8]. Table 4 shows a summary of this data. Bone char was produced in California in 2010. The poultry biochar was made by Josh Frye in 2010. The rest of the chars were produced by JMU students from 2010 to 2012.

Acidity was determined using a simple water wash in a process adapted from Hugh McLaughlin [9]. Two items are notable with pH data: temperature data for the first pine burn listed is unknown and may contain impurities, whereas the second sample was done in much more controlled conditions. For the cedar, which also shows high variability, the first burn is at considerably lower temperature and the trees were from a site with low pH soils. The second cedar sample was from Avalon Acres Farm, pyrolyzed at a higher temperature, and came from a limestone derived soil with a pH above 7.0.

Bone char and poultry char are quite different in terms of structure and content from the wood based biochars. Calling them biochars would be mistaken. These are charred agricultural amendments but lack the carbon and structure that make wood based biochars able to capture nutrients and increase water holding capacity so interesting. The ash content for both these charred inputs is very high, as is their density as a powder. The wood based biochars retain their woody structure and resulting porosity, enabling them to act like a nutrient and water absorbent sponge in the soil.

Table 4 Characteristics of biochars by wood type and temperature of production.

Wood type	Production temperature (°C)	pH	Density (g cm^{-3})	Average ash content (%)
Bone[1]	--	10.90	0.82	90.9
Poultry[1]	--	8.86	0.77	64.9
Pine (2010)[1]	--	8.14	0.27	1.1
Black Walnut[1]	430	6.63	0.30	0.8
Bamboo[1]	465	7.51	0.32	6.1
Pine (2011)[1]	560	5.60	0.30	1.8
Cedar[1]	460	7.62	0.33	3.1
Cedar[2]	600	9.68	0.25	2.0
Sycamore[2]	630	7.87	0.27	2.4

[1]Data from Becker [8];
[2]Data from Decker, Martindale, Najamy-Winnick, Spolarics [7].

Perhaps the most interesting thing about biochar density is its relationship to the heat of production. Fig. 9 contains two scanning electron microscope images of Eastern red cedar, the first produced in 2011 at a temperature of 460 °C, while the second was made in 2012 at a temperature of 590 °C. The difference in density between the two is significant and directly relates to the thickness of the cell wall structure that creates the pores in the biochar. While the thinner cell walls of the 2012 cedar biochar may increase the surface area of the biochar, it exposes a weaker structure that might lead to earlier loss of nutrient or water holding capacity. Further studies are required to make an exact determination.

As part of the characterization process, total gravimetric analysis (TGA) was used to gain a better sense of the exact temperature, the biochars reached during production and to obtain total ash content. TGA involves taking small samples of biochar and putting them through two heating regimes. The first is done in an atmosphere of pure nitrogen to monitor the release of volatiles from room temperature to 700 °C.

The graph in Fig. 10 shows the same sample of cedar biochar made in 2012 as found in Table 4. The inflection point around 590 °C shows an acceleration of mass loss and indicates that the maximum biochar pyrolysis temperature during production was close to 590 °C.

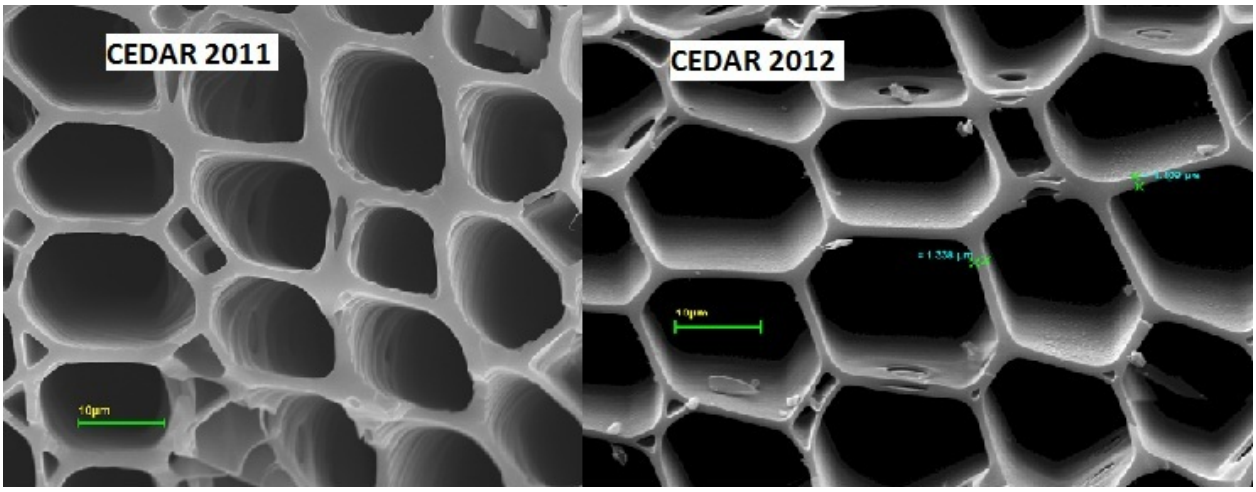

Fig. 9 Comparison of cedar biochars made in 2011 and in 2012. In the 2011 burn the maximum temperature in the inner chamber reached 480 °C and the pore walls were about 1.6 microns thick. In the 2012 burn the maximum temperature in the inner chamber reached 590 °C and the pore walls were about 1.4 microns thick.

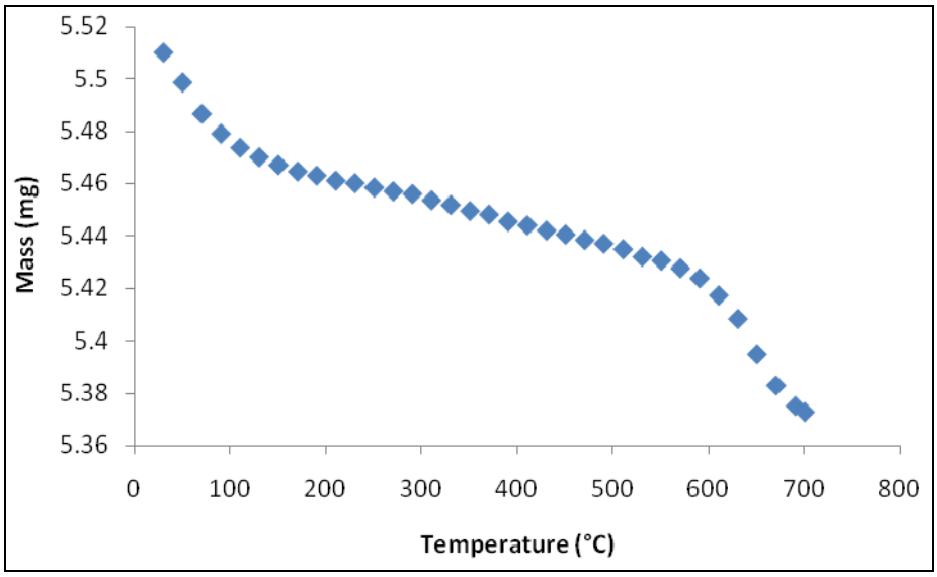

Fig. 10 Total gravimetric analysis of cedar biochar under a nitrogen atmosphere showing the loss of volatiles between room temperature and 700 °C [7].

The second heating regime with TGA uses open air. In this experiment, the carbon of the sample can burn off leaving only ash behind. The curve for this process, again using cedar as an example, is found in Fig. 11. Note that the mass scale for this graph is different from Fig. 10 leading to the long, flat initial portion of the curve, followed by a rapid decline in mass as carbon oxidizes. The final mass reached at 630 °C is the remaining ash content.

The TGA method provides an excellent tool for analysis of biochar and one we have just begun to tap. It should lead to a better analysis of the ash content overall and when used with nitrogen gas will provide superior information on production temperatures. The real benefits will come when we can run the initial wood through the TGA along with the biochar produced from this wood to get a complete picture of mass related to pyrolysis temperature and conditions. Doing this will allow us to develop potential yields of biochar at specific temperatures to compare with actual yields in farm trials, and thus a better picture of the efficiency of our system.

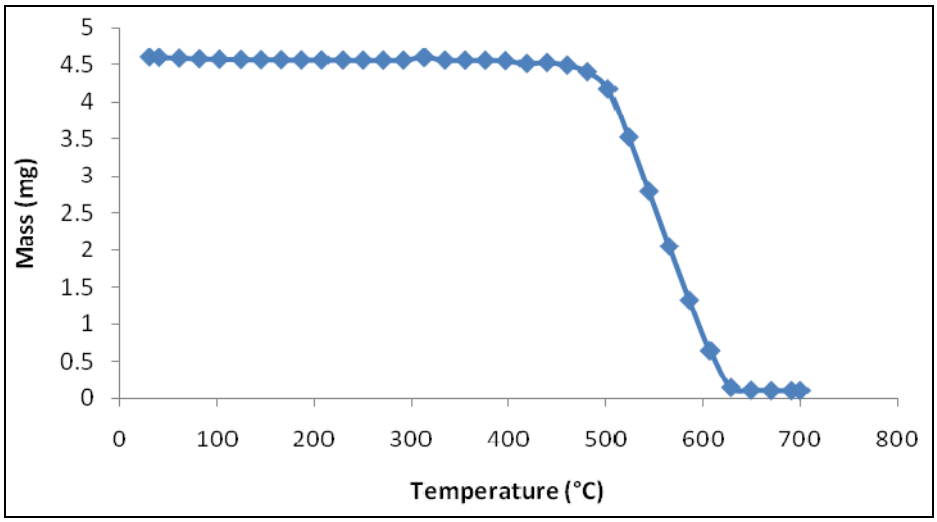

Fig. 11 Shows the cedar biochar in oxygen rich environment during TGA run on 03/16/12 [7].

4. Improvements

As we move toward building and testing of units in high tunnel hoop houses, there are a number of changes we plan to make in the systems. The first involves the door and its support structure. The present door is made of 14 gauge steel sheet metal with a heavy duty piano hinge and an angle iron support to hold dry lay fire brick. This is quite heavy and requires a frame around the entire unit. We would like to move to a much lighter, insulated design with higher gauge sheet metal and lighter a hinge that can be directly attached to strapping steel around the unit. The final design work will be done the fall of 2012.

In high tunnels, the primary goal will be heat capture and slow release to the hoop house to prevent frost damage. Though 500 L of water and 1,000 kg of fire brick holds up to 25% of the energy released on burning, this can be improved. The main option considered is cladding the unit with stone much as done in Tulikivi fireplace designs using soap stone. In our case, we would opt for less expensive fieldstone. By adding this to the sides and perhaps even the top of the unit we can increase overall heat capture and even out the release of energy to the hoop house.

At Avalon Acres the improvements will proceed differently. There the design attempts to maximize heat transfer to the indoor water storage tank. Cladding is unlikely to help, so we are considering options for insulating the entire unit with rock wool and keeping it under a shelter. Rock wool can withstand temperatures up to 850 °C, so would work around the entire unit except for the immediate vicinity of the chimney where we will use more heat resistant ceramic fiber wool. Adding this insulation layer would increase the amount of energy moving into the water tank and then transferring to the indoor water storage tank. Much of this increase would come from the energy originally captured by the firebrick moving into the water tank rather than escaping into the surrounding environment.

We will continue to test the units for their efficiency of production, aiming for a biochar yield approaching 30% by weight of original wood for both fuel and pyrolysis. The goal is to help the end users determine the right ratio of fuel to pyrolyzed wood in the units, so they can load the unit in the evening, light it and leave it overnight. On return, they should find an above freezing hoop-house and a pyrolysis unit cool enough to unload the biochar, but still with slight warmth.

In addition to these field level design concerns, we will also continue efforts to characterize the biochars and improve the products using total gravimetric analysis and scanning electron microscope imaging.

These should help clarify acceptable temperature regimes in the pyrolysis units, achieving a consistent production temperature in the 450 to 550 °C range.

5. Conclusions

Biochar production with heat capture has stimulated the interest of a number of farmers in the Shenandoah Valley. The combination of heat for the hoop houses with production of biochar is more attractive than just one or the other. Plans are underway to construct two more units with other farmers and to continue with measurement and testing of the process.

Present heat transfer of just under 15% of total energy is well below potential yield determined from the initial energy content of the wood. Insulation and better use of fuel for starting pyrolysis will allow for greater heat transfer into the water tank, and hence into the Avalon Acres house. This issue is of less concern in hoop house applications because the heat given off will be with the walls of the hoop house. Greater relevance is the ability to capture more heat in thermal mass. Adding more thermal mass in the form of stone or additional water will help with heat capture and slow release.

While much progress on design and use of the biochar production units has occurred, there is room for improvement. Reducing the total amount of metal used will lower costs for farmers. Our goal is to make an affordable biochar production system for small farms that provides both heat and biochar. In this, we are close to having a replicable design for small farmers.

Acknowledgments

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A number of other contributors helped with different phases of this work. Dr. Robert Prins of James Madison University's Department of Engineering co-advised students during the first year the study. Marlan Showalter of Portwood Farms provided space for that work in 2010. Erich Knight, one of the most knowledgeable local people on biochar, fed me advice from his sources throughout the process. Lorinda Palin and Solly Walker of Avalon Acres Farm provided a great deal support to the four students who put the unit together on their farm. Their enthusiasm for the project and working with students kept us going throughout the winter. Ralph Swartzendruber of Excel Steel helped design the water tank and directed manufacture of all the metal in the units. Dr. Barbara Reisner in the Department of Chemistry assisted with total gravimetric analysis and Dr. Lance Kearns helped with the SEM imagery. Finally, Dr. Jennifer Coffman assisted with editing the final document and was responsible for connecting us with the two farms involved in the project to date.

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