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Evaluation of Small-Scale Sustainable Charcoal Production in Kenya

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Abstract

Woodfuel accounts for 80% of energy consumption in Kenya (World Agroforestry, 2014) and accounts for most of the deforestation after agriculture (KCCAP, 2012). The Drylands Natural Resource Center (DNRC) in Mbumbuni, Kenya is producing sustainable charcoal to combat these issues during a transition to modern energy technologies. Sustainability is defined as supporting a long-term ecological, economical, and social balance. One of the DNRC's goals is to provide charcoal as a community resource for which they can pay farmers in the region a relatively high price for their crop. To accomplish this goal, they need to produce product efficiently to keep production costs low. This research intends to find a way to achieve highest yields in charcoal production at the DNRC. The study focused on the four species most commonly harvested by farmers in the region (*Terminalia brownii*, *Senna siamea*, *Acacia polyacantha*, *Senna spectabilis*). Samples per species n=6, total n=24. These were harvested and dried for 1, 2, and 3-month periods. Moisture, diameter, and weight measurements were taken before carbonization (process of turning wood into charcoal). Mass after carbonization was used to find yield. Observational data were also collected and considered. There was no significant difference in the mean yield of charcoal between species ($\chi^2 = 2.86$, df = 3, p = 0.4137). *S. siamea* and *S. spectabilis* premium charcoal yield was significantly higher than *A. polyacantha* (p = 0.04* and p = 0.008**, respectively). *S. siamea* and *S. spectabilis* had significantly lower yields of briquette charcoal than *T. brownii* (p = 0.008** and p = 0.003**, respectively). There was no significant effect observed for wood moisture or wood dry time on charcoal yield. Samples that incompletely carbonized (did not fully turn to charcoal) had a mean diameter of 4.8 cm. Pest damage resulted in lower quality charcoal.

Keywords: Kenya, Charcoal, Sustainability

1. Introduction

Charcoal is an essential domestic woodfuel that is utilized daily by millions in sub-Saharan African countries. More than 80% of urban households in sub-Saharan Africa rely on charcoal as their main source of cooking energy.[1] While preferred over firewood, charcoal is less bulky, easier to store and transport, has a greater caloric value, and burns without smoke. As many developing nations transition to modern energy technologies, charcoal is an attractive renewable forest resource that can be employed over more inaccessible and expensive gas and electric alternatives.[2]

That charcoal is widely used by households in Africa means a great demand for wood sourced from forest resources. In the 1970s, extensive use of fuelwood as the primary domestic fuel spurred predictions of devastating deforestation and prompted many governments to ban charcoal production.[3] Indeed, sourcing of woodfuel accounts for most deforestation after agriculture,[4] and is mainly associated with forest degradation. Such degradation and selective cutting can deplete preferred species, disrupt ecologically significant microclimates, adversely affect composition and productivity, and reduce biodiversity.[5]

Although charcoal production is viewed as a major contributor to forest resource degradation, it is widely recognized as a positive enterprise for improving livelihoods and alleviating poverty.[6] Many households in sub-Saharan Africa participate in charcoal production to supplement other forms of income, especially in areas where drought and flooding may devastate a household's yield of cash crops. The market for charcoal provides such households with a dependable and convenient energy source at generally stable prices.[7] As urbanization and population growth rises in Africa, the use of charcoal is expected to double by 2030,[8] and remain a vital energy source to many African households.

Production of charcoal is facilitated by pyrolysis, or carbonization, whereby wood that is heated to temperatures above 280°C in the absence of oxygen is reduced to carbonized residue through the decomposition of volatile materials and combustible constituents.[9] Moisture present in the wood prior to carbonization has been recognized to reduce charcoal yield, because of the high energy needed to evaporate it. This additional use of energy is seen as inefficient because it would otherwise remain unburned to create more charcoal.[10] It is recognized that yields are optimal when produced from wood with moisture contents lower than 30%.[11] Thus it is considered more efficient to dry the wood before pyrolysis.

The Drylands Natural Resource Center (DNRC) is a non-government organization in eastern Kenya (Figure 1) that has been sustainably producing charcoal to meet the woodfuel needs of their community. With permission from the local government, the DNRC provides over 450 farmers with resources to grow trees and sustainably harvest them by pruning to obtain wood for charcoal. Farmers sell the green wood to the DNRC, and the organization processes the wood into charcoal using improved efficiency drum and brick kilns. A challenge for the DNRC is that the average yields of charcoal produced from various tree species grown in the community are not known. Typically, farmers are paid according to the fresh weight no matter what kind of species is sold to the DNRC. It would be valuable for the DNRC to know the fair market value of fresh wood delivered by farmers according to the species and their measured charcoal yields. An additional benefit is knowing if wood moisture or duration of wood drying has a noticeable effect on charcoal yield. This would allow the DNRC to determine if they should encourage farmers by offering higher prices for dried wood designated for charcoal production.

The objective of this study is to test the hypothesis that wood conditions and characteristics affect charcoal yield. The variability of charcoal characteristics, such as basic density, wood diameter, and initial moisture content, modify charcoal quality and yield.[12] The yields of charcoal from four important dryland tree species were evaluated; *Terminalia brownii*, *Senna siamea*, *S. spectabilis*, and *Acacia polyacantha*. Moisture content of the wood was measured for wood dried for 1, 2, and 3-month periods. The relationship of charcoal yield with respect to species, wood dry time, and moisture content was analyzed. Wood physical characteristics such as diameter and length were recorded as well as qualitative observations of the samples based on appearance. Diameters of wood samples that incompletely carbonized (did not fully turn into charcoal) were also recorded. The knowledge obtained from this study will provide the DNRC with best production practices and inform the local communities who are trying to improve their personal incomes. This study will also serve as an example for emerging small-scale sustainable charcoal enterprises. The findings will result in recommendations for increasing sustainable charcoal yields for small-scale production at the DNRC.

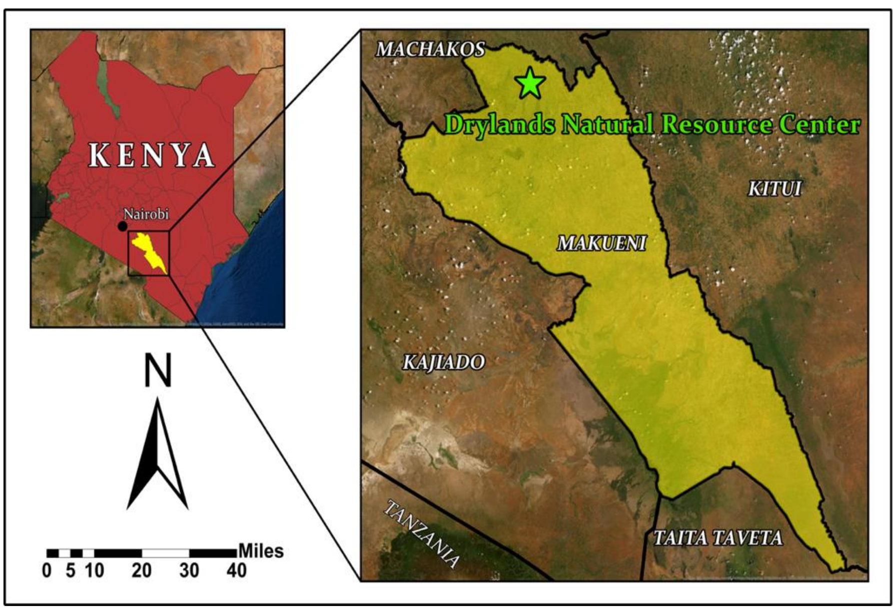

Figure 1. Location of the study site, the Drylands Natural Resource Center.

2. Methods

Fresh wood was obtained from trees of *Terminalia brownii*, *Senna siamea*, *Senna spectabilis*, and *Acacia polyacantha* by pruning. Wood samples from each species were dried for 1, 2, and 3-month periods. Each dry time treatment had two sets of wood samples for all species which resulted in 6 wood samples per species and 24 wood samples total. Each sample consisted of a pile containing many individual pieces of wood from its respective species. The diameters of the individual wood pieces in each sample pile ranged from 0.9 to 9.6 cm with a mean value of 3.02 cm. The pieces were no more than one meter in length. Prior to carbonization, the weight of each wood sample was obtained using a scale with an accuracy of a hundredth of a kilogram. There was great variance in the mass of sample piles (Table 1).

Table 1. Gross dry mass of each sample pile prior to carbonization (kg). Mean = 25.68, SD = 9.16, Var = 83.83

Species	1 – Month (kg)		2 – Month (kg)		3 – Month (kg)	
T. brownii	22.2	19.75	25.2	19.6	42.55	43.34
S. siamea	11	24.65	21.95	22.35	32.35	16.8
S. spectabilis	27.6	17.5	27.65	26.35	26.15	17.5
A. polyacantha	15.85	19.1	48.95	26.35	29.3	32.4

Individual wood pieces within each sample pile were randomly selected to obtain moisture measurements and wood diameter measurements. A caliper with the accuracy of a hundredth of a centimeter was used to measure the diameters of randomly sampled wood pieces. Moisture readings were taken from these pieces with a Delmhorst J2000 moisture meter. The instrument was calibrated and set for genus-specific readings. Pins on the moisture meter were hammered into the center of the wood from the left, center, and right locations of the individual piece to measure conductivity with an accuracy of ±3%. The instrument could only give accurate readings for wood pieces having moisture contents below 40%. To account for this issue, moisture readings from samples were assigned a code associated with the range of moisture values they occurred in (Table 2). Observational data was also collected about the wood samples.

Table 2. Moisture codes used to associate the moisture of an individual wood piece to a range of moisture values.

Code	Moisture Range (%)
1	10-20
2	20-30
3	30-40
4	>40

The wood sample was loaded into a 159L drum kiln and sealed tightly. Larger wood pieces were situated at the bottom of the kiln to ensure complete pyrolysis. A fire was built under the drum kiln to begin the carbonization process. When the kiln reached maximum temperature indicated by pressurized gasses escaping through the tight crevasses of the kiln door (Figure 2), a timer was set for 45 minutes. Following the 45 minute period, firewood under the kiln was taken out and set aside, leaving only the coals to remain. After one hour the coals were removed, allowing for a total carbonization runtime of 2 hours. The kiln was left to cool overnight before opening.

Figure 2. Two drum kilns. Pressurized gasses escape from the sealed door and catch fire during pyrolysis.

The following day, the resulting charcoal was gathered from the kiln. The carbonized bark (also referred to as briquette charcoal) was separated from the carbonized wood (referred to as premium charcoal). The premium charcoal and briquette charcoal were weighed separately on the scale. The recorded masses were added to determine the total yield of charcoal. Any resulting charcoal that did not carbonize completely was rejected and not included in the final recorded charcoal mass. Diameter measurements were taken for these uncarbonized wood pieces.

3. Results

3.1 Charcoal Yield by Species

There was no significant difference in the mean yield of charcoal between species (Kruskal-Wallis rank sum test, $\chi^2 = 2.86$, df = 3, p = 0.4137). Figure 3 gives the percent yield of charcoal between species (%Yield = Premium charcoal(kg) + Briquette charcoal(kg) / Gross dry sample weight(kg) * 100). While *T. brownii* had the highest mean yield of charcoal, there was great variation and margin of error across samples (Table 3).

Table 3. Mean charcoal yields of species and associated standard margins of error. Values in parenthesis indicate standard deviation.

Species	Mean Charcoal Yield (%)	Standard Margin of Error
Acacia polyacantha	24.8 (5.20)	2.13
Senna siamea	25.1 (2.89)	1.18
Senna spectabilis	25.4 (1.85)	0.754
Terminalia brownii	29.5 (7.32)	2.99

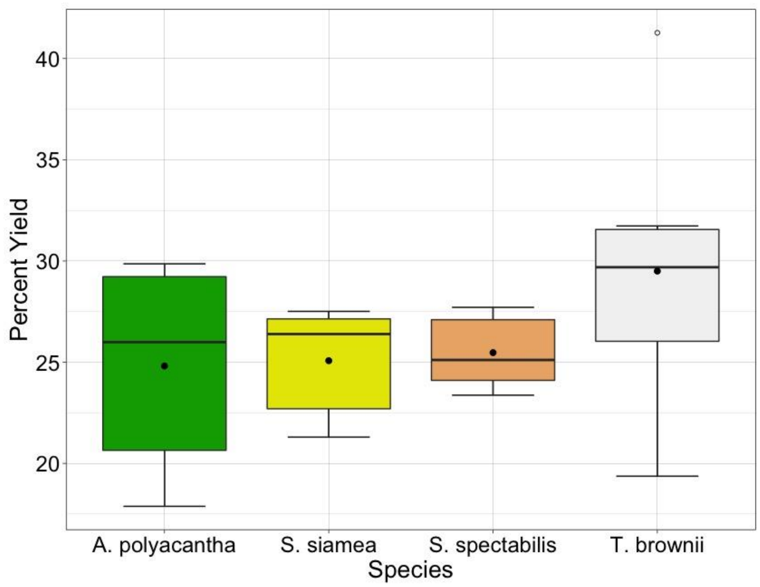

Figure 3. Total percent yields of charcoal for all four species evaluated. Brackets indicate standard error and black dots indicate means. *T. brownii* had the highest yield of charcoal. Large error and variance occur with charcoal yields of *A. polyacantha* and *T. brownii.*

A difference in charcoal quality was observed between species (Figure 4). Premium charcoal was significantly different between species (ANOVA, F = 5.13, df = 3, 20, p < 0.009**), where the yield of premium charcoal was significantly higher with *S. siamea* and *S. spectabilis* over *A. polyacantha* (p = 0.04* and p = 0.008**, respectively).

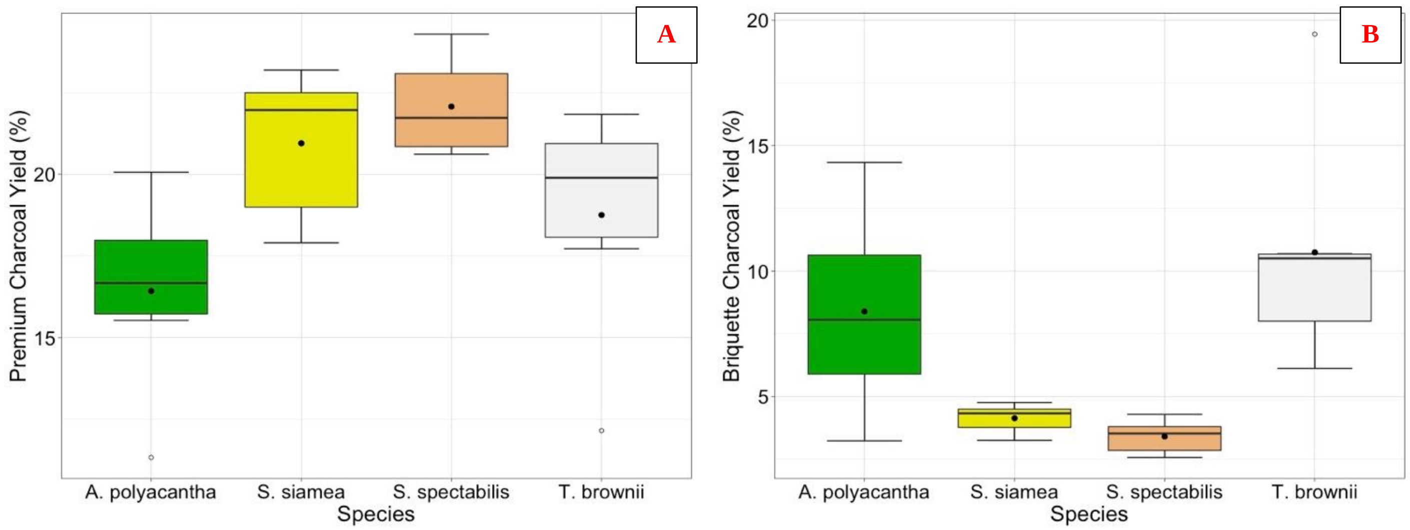

Figure 4. (A) Premium charcoal yields and (B) briquette charcoal yields between species. Brackets indicate standard error and black dots indicate means. *S. spectabilis* and *S. siamea* had highest yields of premium charcoal and the lowest yields of briquette charcoal. *A. polyacantha* had lowest yields of premium charcoal and high yields of briquette charcoal with large error and variance. *T. brownii* also exhibited high briquette charcoal yields.

Briquette charcoal yield was also different between species (ANOVA, $F = 7.54$, $df = 3, 20$, $p < 0.002$**). *S. siamea* and *S. spectabilis* had significantly lower yields of briquette charcoal than *T. brownii* ($p = 0.008$** and $p = 0.003$**, respectively).

3.2 Dry Time and Wood Moisture

Wood dry time and moisture content had different degrees of influence on charcoal yield. Regression analysis showed a weak negative relationship between the moisture content of wood and the total yield of charcoal (figure 5). There was no significant effect observed for wood moisture and the resulting charcoal yield ($F = 1.28$, $df = 1, 22$, $p = 0.27$, $R^2 = 0.01$).

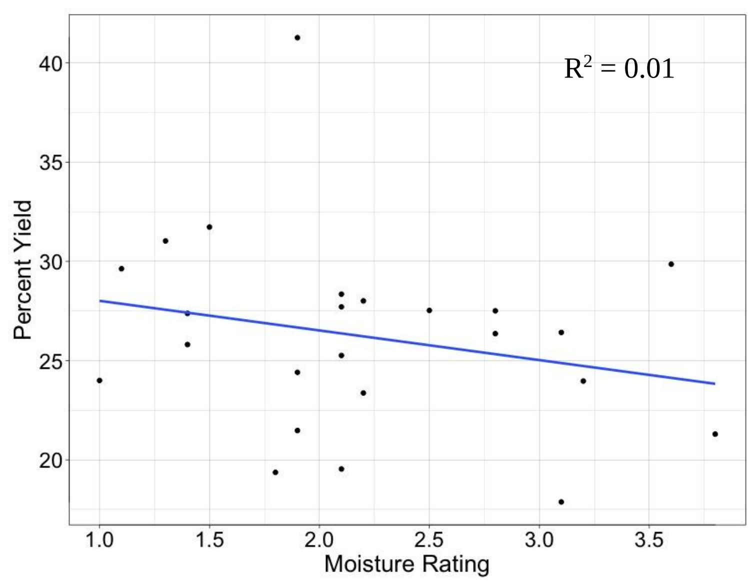

Figure 5. Relationship between total charcoal yields and the average moisture content of its respective wood samples. A negative trend was observed with high residual standard error (4.859).

While different wood dry times were near the significance level for a prominent effect on charcoal yield, the results indicated no significant effect (Kruskal-Wallis rank sum test, $\chi^2 = 5.81$, df = 2, p = 0.054). Figure 6 illustrates the mean charcoal yields for 1, 2, and 3-month dry times. Mean values for yields from the 1 and 2 month dry times were similar, but a higher yield was observed for wood dried for 3 months.

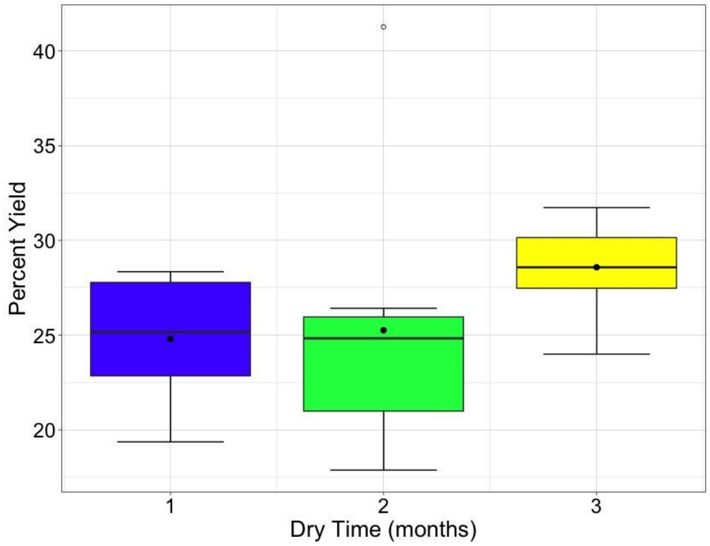

Figure 6. Total charcoal yields according to dry time given in months. Brackets indicate standard error and black dots are means. Highest charcoal yields occurred with 3 month dry times, while no difference was observed between 1 and 2 months.

3.3 Incomplete Carbonization

Some wood pieces did not fully carbonize during pyrolysis. Wood that is not fully carbonized produces undesirable charcoal that is not smokeless.[13] A total of 29 pieces of wood across all sample piles did not completely turn into charcoal. The average diameter of random samples across all piles, which included fully carbonized and uncarbonized samples was 3.02 cm with a range of 0.9 – 9.6 cm. Figure 7 illustrates the diameters and species associations of individual uncarbonized wood pieces gathered after pyrolysis. Samples of *A. polyacantha* were most commonly uncarbonized. A mean value of 4.8 cm was discovered for wood diameters of uncarbonized wood.

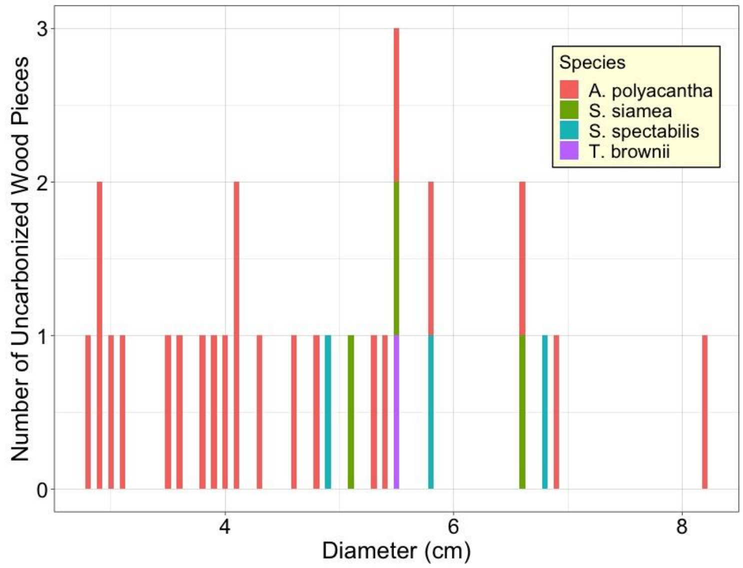

Figure 7. Number of uncarbonized wood pieces associated with a particular diameter and species. Most uncarbonized wood occurred from *A. polyacantha* and diameters between 3.5 and 6 centimeters. Mean diameter of uncarbonized wood was 4.8 cm.

3.4 Observational Data

Observational data explains the difference in charcoal quality between species. *T. brownii* and *A. polyacantha* have branches with far more bark mass than *S. siamea* and *S. spectabilis*. The thin, paper-like bark of the *Senna* species made less briquette charcoal, where carbonization of the thicker bark from *T. brownii* and *A. polyacantha* resulted in more briquette charcoal.

Pest damage to drying wood was observed. 6 wood samples from species of *A. polyacantha*, *T. brownii*, and *S. spectabilis* were observed with pest damage prior to pyrolysis (Table 4). Such damage included an extensive arrangement of small holes in wood created by insect boring, and bigger holes in the wood created by large larvae. The most severe pest damage occurred with samples of *A. polyacantha*, which was subject to both types of damage. Due to the difference in sample size between wood subject to pest damage (n = 5) and wood that was not (n = 19), and lack of control groups (dry time and species type), effect of pest damage on charcoal yield could not be evaluated.

Table 4. All wood samples indicated by associated species and dry time that were subject to observable pest damage.

Species	Dry Time (months)
A. polyacantha	3
A. polyacantha	3
A. polyacantha	2
A. polyacantha	1
S. spectabilis	3
T. brownii	3

Charcoal resulting from wood subjected to pest damage possessed different qualitative properties than wood that was not (Figure 8). Channels created by wood-boring beetles resulted in a very porous and overly friable charcoal. The presence of larvae in wood caused a very sandy and soft textured charcoal. Despite the type of pest, all damaged wood from insects resulted in charcoal that lacked rigidity.

Figure 8. Charcoal resulting from wood of *A. polyacantha* that was subject to pest damage. (A) Wood with severe pest damage resulted in overly friable and sandy textured charcoal. (B) Extensive channels in the charcoal from wood-boring beetles. (C) Larvae (shown carbonized) created significant loss of wood mass.

4. Discussion

4.1 Data Limitations

Due to time and resource constraints, the number of replications for species and dry time treatments were limited to be repeated only twice. Such limitations hampered the acquisition of larger sample sizes and gave reduced power in the statistical analysis. While the data collected showed some significant outcomes and allowed for detailed findings, the low sample size in this study may have been a reason for the absence other significant findings. This would provide an explanation for the findings of a weak relationship between wood moisture and charcoal yield that is inconsistent with the literature. It would also account for the lack of significant findings of wood dry time and its effect on charcoal yield. Continuation of this work at the DNRC will be important for increasing the sample sizes and increasing knowledge of sustainable charcoal production.

The occurrence of uncarbonized wood resulting from incomplete pyrolysis in some samples caused a reduced charcoal yield. The mass of uncarbonized wood in an affected sample was usually less than 3% of the gross dry wood weight in the sample pile. Although this mass of uncarbonized wood was relatively low and not included in the charcoal sample mass to calculate yield, it still caused a yield reduction. This may explain the larger variation in mean charcoal yields of *A. polyacantha*, due to more uncarbonized wood resulting in those species samples.

Wood samples were dried in various areas outdoors that had differing conditions. Wood samples were dried in piles at different locations. Some samples were drying next to active drum kilns, others may have dried in direct sunlight, while some were drying under the shade of the tree canopy. Heat taken up by wood from sunlight or active kilns may have dried the wood faster than samples situated away from kilns or under shade. The variation in the initial sample pile mass was great (Var = 83.83, SD = 9.16). This may have affected the drying rate between piles. Uneven drying dynamics across samples may have implicated total wood moisture content and its relationship with dry time. In light of this, wood dried for longer may not have necessarily had a lower moisture content.

Moisture content showed little to no effect on yield of charcoal in this study. The instrument sensitivity to only the moisture readings below 40% may have implicated these findings. This issue in the methodology may have made it difficult to more accurately identify the true relationship between wood moisture and the resulting charcoal yield. That wood moisture above 40% was not precisely measured created a great margin of uncertainty. Additionally, the rating of moisture values according to a range may also have disguised a more clear relationship. Future studies should assess moisture with instrument sensitivities above 40%.

4.2 Recommendations

4.2.1 production with species

While no significant differences were observed for charcoal yield between species, production should be maximized with wood from species according to availability and the resulting charcoal characteristics. The significant findings of differing yields according to charcoal quality between species is an important observation. *S. spectabilis* and *S. siamea* had highest yields of premium charcoal, and lowest yields of briquette charcoal (carbonized bark). It is widely recognized that charcoal produced from bark contains higher concentrations of ash and other constituents that cause a greater production of smoke and a shorter burn time.[14] *T. brownii* is the wood preferred at the DNRC due to its perceived charcoal quality. According to DNRC staff in the tree nursery, species of *Senna* are much faster growing than species of *T. brownii*. Since *S. siamea* and *S. spectabilis* produce less briquette charcoal, and their branches grow faster than *T. brownii*, it would be advantageous for the DNRC to maximize production with *Senna* species for highest charcoal quality and a faster recovery of wood resources.

Production of charcoal with *A. polyacantha* should be minimized for several reasons. Wood from *A. polyacantha* was most commonly uncarbonized. Samples from *A. polyacantha* had lowest yields of premium charcoal and highest yields of briquette charcoal. Furthermore, the species is most vulnerable to pest damage which degrades wood and reduces rigidity and charcoal quality. Indeed, wood-boring beetles have been recognized as a threat to freshly cut timber from *Acacia* species.[15] A study of wood-boring beetles found that cut timber infested with wood-boring beetles in *Acacia xanthophloea* reduced wood mass by a mean of 34%.[16] *A. polyacantha* should be the last resort as a material resource if wood from no other species are available to use for charcoal production.

4.2.2 production improvement and infrastructure

Although a weak relationship was discovered between wood moisture and charcoal yield, the results suggest there may be a relationship between dry time and charcoal yield. It is logical to assume that a drier specimen would lead to more efficient charcoal production. Wood dried for 1 and 2 months had lower yields than wood dried for 3 months. For this reason, it is suggested that the DNRC dry fresh wood for at least 3 months to maximize charcoal yields. Albeit there are costs to letting wood piles dry for extended periods of time such as space requirements and potential for insect infestation.

To address the issue of uneven drying dynamics and reduce exposure to pests, it would be highly advantageous for the DNRC to build a solar drying structure out of simple and cheap materials. The heat trapped by sunlight may assist the drying of wood and improve charcoal yield. The encasement of wood under a plastic material may prevent insects from easily accessing and degrading the quality of the wood. Standardizing the gross weights of the harvested wood piles before carbonization may also contribute to reducing the disparity in drying dynamics between the piles.

Incomplete pyrolysis is a barrier to maximizing charcoal yield. To prevent wood resources from inadequately carbonizing and ultimately being wasted, wood pieces with diameters at or above 4.8 cm should not be used for charcoal production in the drum kilns. Instead, they should undergo pyrolysis in the much larger brick kiln that is employed at the DNRC (Figure 9). That the brick kiln has a greater loading capacity for wood and retains high temperatures for long periods of time makes it more suitable for pyrolysis of large pieces instead of the drum kilns.

Figure 9. DNRC staff unloading charcoal from the larger brick kiln. This kiln type is suggested for use with larger diameter wood pieces of 4.8 cm or greater rather than the drum kilns used in this study.

5. Conclusion

Differences in the yield of various charcoal types between species supported the hypothesis that wood characteristics and conditions affect yield. While a weak relationship between wood moisture and charcoal yield did not support this hypothesis, as well as the lack of significant results of dry time and charcoal yield, the low statistical power due to a small sample size indicated that more data is needed to better support or reject the hypothesis. It would be advantageous for the DNRC to focus charcoal production with *Senna* species to maximize charcoal yields and produce higher quality charcoal. Drying wood for at least 3 months may provide an added benefit. Production with *A. polyacantha* would be undesirable due to the effect of wood-boring beetles, incomplete carbonization of wood, and high yields of briquette charcoal. Monitoring charcoal yields by the DNRC according to different species and dry times will be important to continue increasing knowledge of small-scale sustainable charcoal production. Furthermore, the small-scale model employed at the DNRC will remain essential for encouraging sustainable and responsible production of charcoal. As the demand for charcoal grows with urbanization and population growth, sharing this knowledge of charcoal production will continue to be ever important.

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