The Potential for Biochar to Improve Sustainability in Coffee Cultivation and Processing: A White Paper

International Biochar Initiative

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EXECUTIVE SUMMARY

As the security of the coffee supply is threatened by climate change and other environmentally induced pressures such as mudslides and erosion, a focus on sustainable coffee production is gaining increased attention in many areas of the world. At the same time that coffee production is under pressure from climate change impacts, coffee cultivation and processing leads to greenhouse gas (GHG) emissions, contributing to climate change. With more and more consumers shifting their buying habits to support products with lower climate and ecosystem impacts, coffee supply chain participants increasingly seek ways to reduce their carbon footprint and improve the sustainability of their overall growing and processing practices.

Biochar is a solid material obtained from the thermochemical conversion of biomass in an oxygen-limited environment. Biochar can be used as a product itself or as an ingredient within a blended product, to improve soil properties and/or resource use efficiency, to remediate and/or protect against environmental pollution, and as an avenue for GHG mitigation (*IBI, 2013*).

This paper reviews some ways that biochar is being incorporated into coffee production and coffee processing systems to improve overall economic and environmental impacts, with a focus on processes typically performed at or near the site of coffee cultivation. It includes certain findings related to potential benefits of adding biochar to soils including improved soil fertility, disease management and composting; outlines how the use of biochar can reduce negative impacts related to waste water from coffee processing; highlights opportunities for optimizing the use of coffee residues as potential feedstocks for biochar; and suggests pathways the coffee industry can use to decarbonize its supply chain including the use of renewable energy.

The methodology used in this paper combines a review of the peer-reviewed literature with a survey of selected coffee and biochar demonstration projects in various coffee growing regions around the world. Several project teams were interviewed on different continents and project descriptions are included which outline preliminary results and other details from field trials using biochar in coffee production.

Although an increasing number of coffee growers have demonstrated promising results from the use of biochar, knowledge about the benefits of carbonizing coffee residues and using

biochar in coffee cultivation is still low. While more coffee and biochar projects are underway, peer-reviewed scientific publications on this topic are few, and many studies focus on coffee residue management and not biochar impact on yield. Recommendations for future research are highlighted in the *Next Steps* section. Progress has been made on a few recommendations from the previous white paper; 1) a methodology for biochar trials on coffee plantations has been drafted and 2) progress has been made on characterizing different types of carbonized coffee residues. However, a few recommendations; 1) creating standardized Cost/Benefit Analysis (CBA) approaches to better quantify the benefits of biochar use in coffee production and processing; and 2) increased coordination between existing coffee and biochar projects to share information and identify lessons learned and best practices; have not seen much progress due to a lack of funding for these activities.

New recommendations for future activities include increased education, more comprehensive coffee and biochar demonstration projects including on-farm biochar production, agronomic evaluation, quantification of economic and social impacts, optimization of biochar and coffee residue composting and quantification of carbon drawdown potential for coffee growers and processors have been added. If these demonstration projects used a similar method for trial design, best practices could be more easily identified and shared.

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THE COFFEE GROWING CHALLENGE

Global agricultural operations are increasingly impacted by erratic weather patterns attributed to climate change. Coffee, one of the most highly traded agricultural commodities in the world, is already being negatively impacted by increasing climate variability with far-reaching effects on soil water contents, disease pressure and nutrient losses, potentially leading to increased fluctuations in yield and price.

Coffee production for 2016/2017 is estimated at 157.4 million bags (each containing 60 kg of coffee beans), up from 145.1 million bags in 2012/2013 (International Coffee Organization) with more than half sourced from the top two producing countries: Brazil and Vietnam (Figure 1). It is grown in over 70 countries and provides

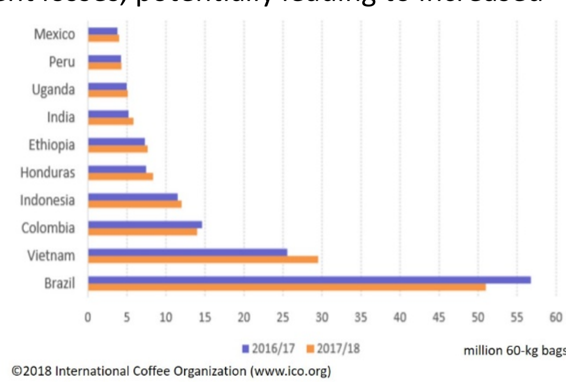

Figure 1: Coffee Production 2016-2018; Source ICO

a livelihood for more than 25 million coffee producers, 80 percent of whom are smallholder farmers (Fairtrade, 2018).

Many smallholder coffee growers have limited access to improved farming techniques and adaptation technologies, rendering their livelihoods at risk due to predicted worsening of negative climate effects which expose both the coffee farmer and the companies they supply to high levels of risk. A decrease in yield for these farmers can be catastrophic, potentially causing them to abandon farming altogether and forcing coffee laborers to seek work outside the coffee sector (Edgerton *et al., 2013*). In some areas, more extreme weather events cause topsoil loss through erosion, while in other areas increasing droughts reduce yield. Imbach *et al.* (2017) predict that the combination of climate change and pollinator decline could reduce land suitable for coffee growing by 73 – 88% globally by 2050. Many coffee growing regions have seen significant yield losses in recent years due to coffee leaf rust (*Hemileia vastatrix*), often called roya, a parasitic fungus which lowers yield and can eventually kill coffee plants. Central America alone suffered damages of close to USD 500 million (approximately 2.7 million bags of lost production) from coffee rust in 2012 –2013 (*International Coffee Organization Annual Report, 2013*). Other pests, diseases and fungi are becoming more prevalent in some regions particularly areas with fewer cold snaps that formerly helped to reduce incidence of pests.

Although there are increasing efforts to move towards sustainable production methods, coffee, like many crops, can have a substantial carbon footprint due to input requirements of fertilizer, energy, and water from cultivation to cup. In some coffee cultivation regions, there is a growing use of pesticides to control the coffee berry borer (*Hypothenemus hamperi*) and coffee leaf rust. At the same time many growers have increased the use of fertilizers (United Nations, 2004) to boost yields in nutrient-poor soils, which can have negative environmental and human health impacts if used in excess and contrary to recommendations. In addition, the untreated release or burning of coffee residues can cause air and water pollution and is a source of GHG emissions (Coltro *et al.,* 2006). Some coffee producing regions use few to no chemical fertilizers for crop growth or pesticides but could take advantage of biochar to increase crop yield and soil health and reduce GHG emissions.

More consumers are seeking sustainably produced agricultural products. To meet this demand, a wide range of certification programs have arisen that require implementation of best management practices in social and environmental realms for coffee cultivation. Certification programs may be run by independent third parties (e.g. Bird Friendly, Rainforest Alliance, Organic, Max Havelaar, Fair Trade, UTZ Certified, 4C, etc.) or individual coffee companies (e.g. Starbucks and Nespresso). Several of these programs require farmers to pay for certification, auditing, and investments in new technologies to meet various standards, and these costs may not necessarily be entirely offset by increased revenues. However, many of the environmental and social benefits from the programs are seen as beneficial by not only consumers but also coffee farmers and communities. Increased premiums or buyer retention for certified coffee can give growers an incentive for investing in the coffee farming communities (Taylor, 2007). Those certification programs that also promote or result in positive impacts on yield may be more attractive to growers (Barham *et al.*, 2011).

BENEFITS OF PRODUCTION & USE OF BIOCHAR FOR COFFEE PRODUCTION

Biochar, at its most basic, is carbonized organic material. It can be produced using a wide variety of thermochemical conversion technologies, and from a wide variety of feedstocks. Although most often biochar is intended for direct use in soils as a soil amendment to improve soil functions and water-holding capacity and to reduce land degradation, there are other uses for biochar which can benefit the coffee industry across the entire supply chain (Figure 2). For example, biochar production can provide a highly sustainable method for managing residues as well as generating clean, renewable, decentralized energy. This unique combination of benefits makes the use of biochar in coffee production valuable from both a climate change mitigation and climate change adaptation perspective.

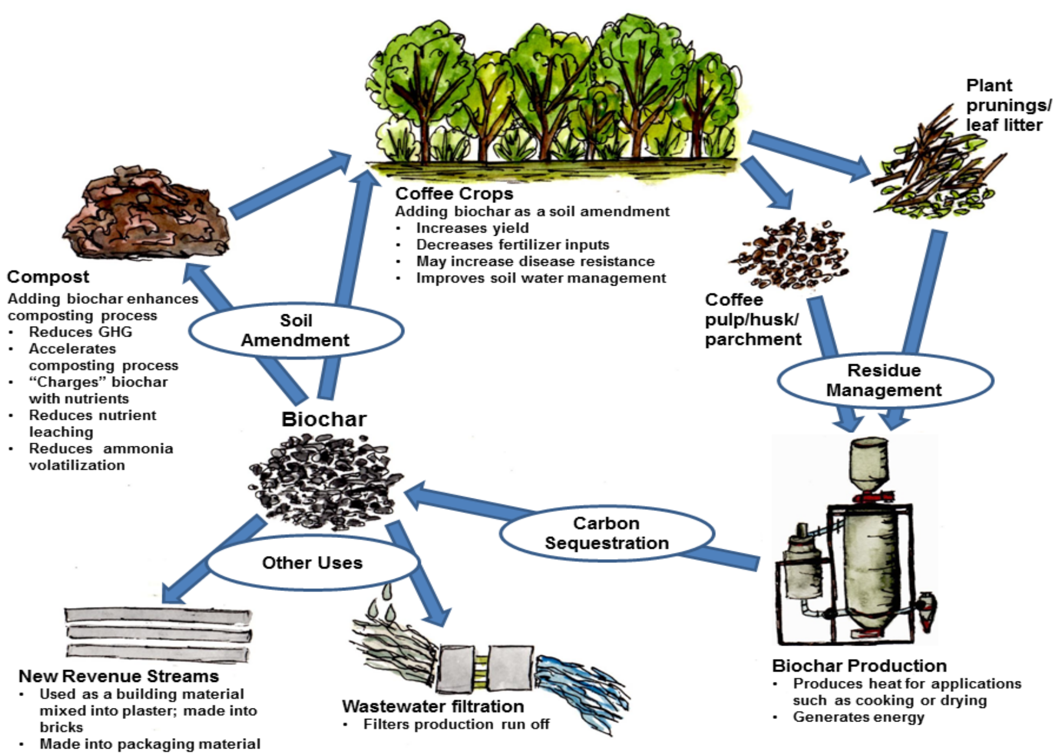

Figure 2: Biochar integration into a coffee production system, and potential impacts; source: Thayer Tomlinson, 2015

Increasingly, coffee and biochar projects are using biochars made from coffee residues though some are using other feedstocks. Characterization of coffee residues-derived biochars has advanced over the past few years. However soils, weather patterns, and cultivation techniques vary widely. To date there is still insufficient biochar trial data to predict impacts on coffee yield or tree growth rates. Nonetheless, there is a growing body of experience which supports the use of biochar in coffee cultivation and coffee processing operations, to improve the sustainability of the entire supply chain. This paper highlights some of the many benefits of carbonizing coffee residues and using the resulting biochar within the coffee growing and processing industry. Information from studies using biochar made from biomass other than coffee residues and applied to other crops is also examined to illustrate general findings and highlight potential benefits, based on sound research, but that may not have been studied yet in coffee cultivation.

Soil Amendment

When added to the soil, biochar is generally considered a soil amendment and a carrier for nutrients, but not a fertilizer. However, biochars with relatively high nutrient content that were produced from nutrient-rich feedstocks, such as manure, may be considered fertilizers. Most biochars do not contain significant amounts of nutrients needed by plants but develop a high nutrient holding capacity. In addition, various other properties of biochar can help improve different soil functions, soil fertility and soil health. One such characteristic of most biochars made from woody or leafy material is their high porosity which can improve water management properties of soils. Coffee plants do not tolerate saturation in the rooting zone. With the potential for increased heavy rains in some coffee growing regions, soils could become waterlogged, potentially causing a decline in yield and plant health. Another effect of climate change is the increased variability of precipitation. For farmers in some areas, this may require the installation of irrigation systems to maintain plant health during dry periods. Biochar from vine prunings has been shown to improve water holding capacity in perennial cropping systems (Baronti *et al., 2014*). In addition, biochar made from white lead trees (*Leucaena leucocephala)* has been shown to improve certain physicochemical properties of highly weathered soils which may help to reduce erosion (Jien *et al., 2013*). It can also facilitate rebuilding soil when heavy rains wash away fertile topsoil.

Although coffee plants tend to prefer slightly acidic soils, some coffee growing regions have soils that are too acidic or have generally poor nutrient levels. Many biochars have a high pH and can have a liming effect in soils which can reduce the need for off-farm inputs of lime. In addition, biochar generally develops a high cation exchange capacity (CEC) which can improve the soil's ability to retain many nutrients (Reddy *et al., 2013*). This not only reduces the amount of fertilizers required but can also reduce leaching of excess nutrients into local waterways. Biochars may also reduce leaching of nonpolar pesticides and herbicides (*Kookana, 2010;*

Delwiche *et al., 2014*) especially if they strongly adsorb to biochars with high surface areas (*Cabrera et al., 2014*). However, this same effect may also reduce pesticide or herbicide efficacy (Tang *et al., 2013*).

The high nutrient holding capacity of biochar makes it suitable to be charged with organic waste nutrients such as compost, manure, or animal/human urine which may be a freely available fertilizer to small coffee farmers. When thoroughly mixed, the organic nutrient solutions enter the biochar's porous system and are prevented from leaching out when applied to soil. These organic, fortified biochars become slow release fertilizers and can provide continuous plant essential nutrients, particularly nitrogen, without the risk of ground water contamination (*Kammann et al., 2015*).

Disease Management

Warming temperatures are aiding the spread of pests and pathogens across the globe. Coffee leaf rust, also known as roya, a fungus that has caused great damage to arabica coffee trees, is an increasing threat to coffee growers particularly in Central and South America. Preventing and controlling rust takes many forms including selecting resistant varieties, proper cultural management (e.g. provision of sufficient nutrients, pruning, etc.) and chemical treatment. Biochar may be beneficial in controlling rust and can also help mitigate some of the negative impacts caused by using chemical controls.

Pruning is strongly encouraged as a means of controlling fungal spread. However, pruning alone is not sufficient as spores can still spread from pruned leaves, especially during the wet season. Carbonizing infected leaves and branches is an effective agricultural practice to eradicate spores and minimize transmission.

Proper nutrient supply and pH management can help coffee trees fend off leaf rust and other diseases. Blending organic or chemical fertilizers with biochar can reduce nutrient leaching and render nutrients more available to plants over a longer period as compared to when fertilizer is applied without the benefit of a highly porous carbon structure. Often nutrients in fertilizers are leached or eroded due to heavy rains, leading to wasted money and polluted streams, wetlands and aquifers. Due to its capacity to retain nutrients, biochar offers a way to reduce fertilizer costs and negative impacts caused by leaching and runoff. It can also help reduce soil acidity leading to better nutrient availability. Unfavorable soil pH can encourage propagation of fungi such as leaf rust, so maintaining optimal pH (6.0 – 7.5) is a critical disease management strategy.

While many coffee farms were organic by tradition or economic necessity, the devastating onslaught of coffee rust has caused some farmers to lose the sick plants in that season or turn to fungicides as one of a variety of different disease management strategies. Organic options include copper-based fungicides which cover plant tissue and block respiration and protein production within spores. Although copper-based fungicides are sprayed on plants, they do not enter plant tissues. It should be noted that copper-based fungicides are some of the most toxic and persistent (Bünemann, 2009) and can lead to long-term negative impacts on soil fertility and biota. Some research is beginning to show the biochar can be used to immobilize Cu in agricultural soils (Cardenas-Aguiar, 2017).

A group of chemical fungicides called triazoles act as both a preventive and curative fungicide at least in the early stages of a coffee rust outbreak. For larger infections, fungicides within the strobilurins family are recommended. However, these toxins may be responsible for increased resistance to fungal remedies for humans (Bastos, 2018), and so these chemicals should be used with caution and their spread contained whenever possible. Biochar can help with containment in a few different ways. Biochar made from rice straw can be used to filter water contaminated with pesticides (Taha, 2014) and some woody biochars have been shown to immobilize pesticides in soils (Yu, 2010). Cheng et al. (2017) showed that biochar made from tobacco stalks can increase the population of bacteria capable of degrading pesticide pollutants while also decreasing plant uptake of the toxins. There is even evidence to suggest that compost containing biochar may contain antifungal properties (Sehar, 2017), though this has yet to be tested against fungi that impact coffee.

Researchers from the Indonesian Coffee and Cocoa Research Institute were looking for more sustainable alternatives for nematode control in coffee plantations. Chemical control of the roundworms is expensive and can kill off beneficial microflora and impact groundwater supplies. In an in vitro study, Rahayu *et al*. (2017) found that an application of 4% woody biochar per Ml of water was able to significantly reduce populations of the parasitic nematode *Pratylenchus coffeae* in petri dishes. These root-lesion nematodes lead to reduced uptake of water and nutrients and can lead to stunting and leaf shedding.

The same researchers found that an application rate of 2% woody biochar per Ml of water benefitted young Arabica coffee seedlings more than 3%, 1% or 0.5% biochar application rates in terms of higher fresh weight of roots (14%), shoots (18%) and dry weight of shoots (21%).

Composting

Many coffee producers compost pulp and other by-products of coffee production as a means of residue management. Compost can be a valuable soil amendment for application to crops. For those producers that do compost such as the Kaweri Coffee Plantation in Uganda (Figure 3), adding from 10 – 30% biochar (w/w) can provide a number of advantages (Sanchez et al., 2017).

Biochar added to compost for a few weeks becomes pre-charged with nutrients adsorbed from the compost and can be added to soils as a nutrient carrier. Using biochar in compost also enhances the surface of biochar leading to improved CEC which increases nutrient holding. It can also increase micropores in biochar which increases adsorption capabilities (Sanchez et al., 2017).

Figure 3: Biochar enriched compost production at Kaweri Coffee Plantation in Uganda.

Biochar has been found to accelerate and improve the composting process—mainly increased temperature which stimulates microbial activity. This increased activity and temperatures can also reduce certain pathogens though it is unknown what happens to caffeine and tannins in pulp when temperatures are increased. Biochar addition during composting has been shown in both research and commercial operations to reduce labor for turning piles and improve habitat for microorganisms, enhance moisture, aeration and nutrient availability thereby boosting microbial growth (Sanchez *et al.,* 2017). This may have important economic implications since accelerated composting is a desirable effect, especially with organic materials that require long composting times and take up space at coffee operations.

Biochar addition to compost has been found to reduce emission rates of methane (CH_4) and nitrous oxide (N_2O) which result from the composting process (Wang *et al., 2013*), and reduce nitrogen losses including ammonia which can cause nuisance odors (Bernal *et al., 2009*).

FILTRATION

The amount of water needed for coffee cultivation is relatively high, but the amount of water needed for depulping, fermenting, and washing beans can be even more significant depending on the process and relative age of the processing equipment. Some estimates put the amount of water between 1 m^3 – 20 m^3 per ton of fresh coffee cherry processed (Blinova *et al.,* 2017). Untreated coffee processing wastewater is typically very acidic, as low as pH 4, with high levels of organic matter (i.e. pulp and mucilage) and, when released into waterways, can negatively impact aquatic ecosystems. Some of the organic matter also contains tannins, caffeine and other potentially toxic elements.

Biochar shares many characteristics with activated charcoal which is often used in water filtration. Using biochar to treat effluent from coffee processing can not only help reduce organics in wastewater, but some studies have shown that certain enhanced biochars can remove significant amounts of nitrogen, phosphorus and other nutrients (Li *et al.,* 2017).

Activated charcoal filters have been used since 1933 as one of four main processes to decaffeinate coffee. The process is known as the Swiss Water Process. Once saturated, it is feasible to regenerate the carbon by heating it to at least 650°C. However, this method eliminates the possibility of harvesting the caffeine which has value as a food and beverage ingredient. It remains to be seen if biochar made from coffee residues could fulfill this same function with similar efficacy. However, researchers have shown that carbonized pineapple leaves can be effectively used to filter out caffeine, an emerging contaminant of concern, from aqueous solutions (Baltrame *et al.,* 2018).

It is also unknown if the caffeine-saturated biochar could be utilized in the ever-increasing number of trendy foods and drinks that are tinted with activated charcoal, potentially providing an energy boost in addition to the purported cleansing properties.

Energy Production

Thermo-chemical conversion technologies capable of creating biochar include pyrolysis and gasification. Pyrolysis thermally decomposes biomass without the presence of oxygen to create biochar at temperatures starting at 300°C. Gasification uses limited oxygen and higher temperatures (500°C – 1,500°C) (Lehmann *et al*., 2015). A co-product of biochar production is energy in the form of process heat, liquid fuel, or combustible gases that can be used to supply heat or electricity.

Coffee milling stations require large amounts of energy; procuring sufficient, affordable energy can be challenging in certain remote areas. Using coffee residues to generate heat for drying or power (2.7 MWh per ton dry waste are available, 1.8 MWh will stay in the biochar) for other processing tasks replacing wood or fossil fuels while simultaneously reducing residues in an environmentally beneficial manner. Replacing fossil fuel generated electricity within the coffee industry with renewable electricity produced in the pyrolysis biochar system could also help reduce the carbon intensity of coffee production – or perhaps even make it carbon negative.

Using data from a pyrolysis pilot project in Vietnam (see project summary p29) 2.5 t wet pulp or 0.7 t of dry pulp are produced for every ton of raw dry coffee bean. This biomass contains about 3.2 MWh of energy – of which 40% will remain in the biochar and 60% becomes available to generate heat or combined heat and power. Using a typical system efficiency of 85%, 1.6 MWh of energy is available per t raw coffee bean – which should be sufficient for coffee drying.

When using the heat generated during pyrolysis to generate power, net electrical efficiency is low, approximately 15%. Given that, utilization of heat will remain an important part of the business case and energy balance.

BIOCHAR FROM COFFEE RESIDUES

The amount of coffee residues from cultivation to cup exceeds the total weight of the coffee cherry harvest when tree prunings and leaf litter are taken into consideration. Much of the waste biomass is difficult to utilize for a variety of reasons and often ends up having a detrimental impact on the environment. Addressed below are the various types of coffee residues that could be converted into biochar and the benefits and challenges related to each (Figure 4).

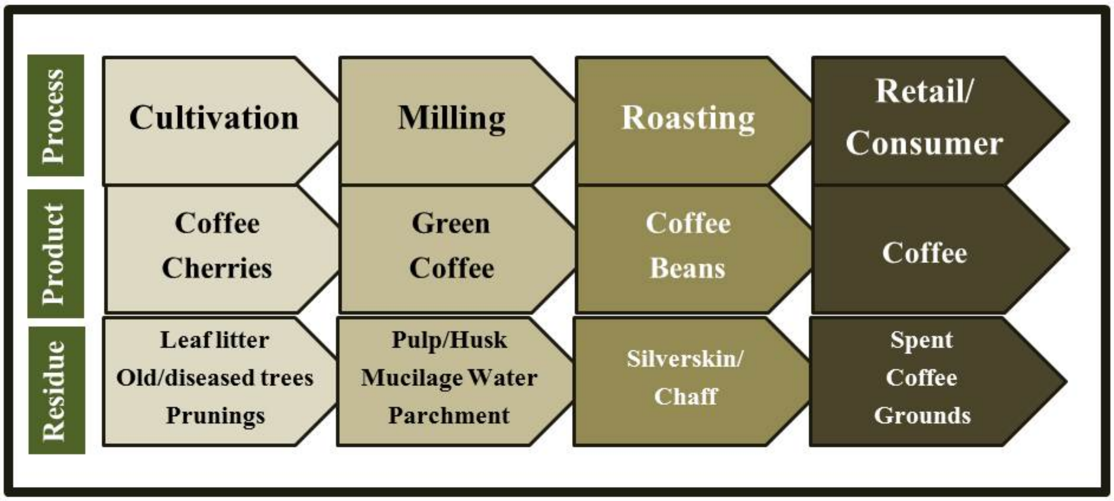

Figure 4: Coffee processes, products and residues.

Prunings and leaf litter

Coffee plants are pruned to maintain ideal quality of yield and tree height for harvesting. The amount of pruning material varies greatly depending on: number of plants per hectare, coffee variety, whether plants are grown in sun or shade or on steep terrain, monoculture or polyculture, desired tree shape, etc. Pruning involves removal of suckers as well as unproductive or excess branches. In sun-grown monoculture plantations, prunings may average 1 ton ha^{-1} $year^{-1}$ whereas in shade grown or polyculture plantations the amount can be 4 – 5 times larger when the biomass from surrounding shade trees is included.

The amount of coffee leaves (leaf litter) per hectare can be substantial, especially in shade grown systems. Often the litter remains on the ground and is used for mulch, composting, or to suppress weed growth. Removal of coffee leaf litter, at least on an occasional basis, may prove beneficial as caffeine from coffee leaves can leach into soils and reduce productivity (*Weinberg et al., 2002*). In addition, removal of disease impacted leaves may reduce the spread of fungal diseases.

During one study in Kenya, Alvum-Toll *et al. (2011*) analyzed the nutrient content of biochar made from coffee leaves as compared with biochar made from other feedstocks such as maize stover, coconut leaves, cassava stems, and banana leaves (Table 1). Coffee litter-derived biochar had significantly higher nitrogen than all other biochars and only biochar from fresh banana leaves had higher levels of potassium.

Table 1: Carbon and nutrient concentrations in biochars from various feedstocks;
Source: Alvum-Toll *et al*., 2011

	Macronutrients (as % of total)						**Micronutrients** (ppm)					
Plant material	**C**	**N**	**P**	**K**	**Ca**	**Mg**	**Mn**	**B**	**Zn**	**Fe**	**Cu**	**Na**
Fresh banana leaves	51.2	1.05	0.16	8.68	1.83	0.76	1637.0	20.80	126.20	2762.0	15.01	706.8
Maize stovers	52.2	0.58	0.10	1.03	0.64	0.50	363.7	4.63	137.40	5368.0	11.31	573.2
Wilted banana leaves	54.0	1.37	0.12	0.55	4.13	0.72	7348.0	32.93	325.50	2298.0	10.75	570.6
Coffee leaves	**54.1**	**2.63**	**0.27**	**4.80**	**3.33**	**1.01**	**1305.0**	**141.00**	**211.70**	**6019.0**	**123.80**	**1026.0**
Coconut leaves	61.0	0.47	0.10	3.00	1.29	0.55	390.0	28.03	62.25	349.5	6.45	9497.0
Cassava	60.8	1.73	0.31	4.01	3.22	0.99	387.9	20.35	75.46	209.5	11.75	777.9

In addition to normal maintenance pruning, most coffee trees undergo extensive rejuvenation pruning every 6 – 10 years to reverse yield declines. This, in addition to the removal of diseased or damaged trees, produces a considerable amount of biomass per hectare, all of which could be utilized as feedstock for biochar production.

Coffee Pulp, Husks, Hulls

Only a small fraction of the harvested fruit (cherries) ends up being consumed, leaving a large amount of residues to manage. Coffee cherries are comprised of several parts in addition to the coffee beans (Figure 5), but often little of the non-bean portion of the cherry is utilized due to the high concentration of caffeine and tannins which renders this material difficult to use for livestock feed or soil amendments.

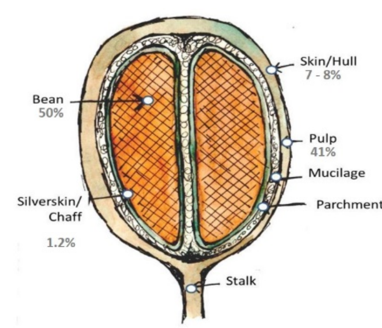

Figure 5: Coffee bean schematic

The first step in coffee processing involves removing the skin, stems and pulp. Coffee can be processed in either a wet or dry system. In wet processing, the portion that is leftover is referred to as pulp. Left on its own, wet pulp is very acidic and can cause several environmental problems including water contamination if disposed of near waterways. This can result in methane and nitrous oxide emissions from anaerobic decomposition of the organic material. In some areas, coffee pulp is composted. While composting also provides benefits there can be significant GHG emissions depending on the method used. Pulp may also provide a breeding ground for pests and pathogens as well as cause significant odor issues from the decomposing feedstock.

Figure 6: Coffee pulp; from http://theplantationdiaries.typepad.com/the_plantation_diaries/el-salvador

The typical high moisture content (>80%) of pulp (Figure 6) can present a challenge to converting this material into biochar, but biochar production technology exists that can handle high moisture content feedstocks or the heat produced during carbonization can be utilized to lower the moisture content. In addition to reducing the sheer volume of leftover residues, carbonizing pulp could reduce pests, pathogens, odors, and GHG emissions.

Estimates from Brazil for coffee pulp production are roughly the equivalent to the amount of coffee beans produced (49 million bags in 2016, i.e. 2.9M metric tons). Much of the pulp is land applied to add carbon and nutrients to soils. However, this practice can lead to population increases of insects which can harm humans and livestock. Carbonizing pulp (Figure 7) would eliminate that problem while slowing the return of carbon to the atmosphere. Biochar made from coffee pulp is relatively high in K which could lower or replace imported sources of potassium. It also has high CEC as compared to other types of biochar which can increase nutrient holding capacity of soils, leading to reduced fertilizer requirement (Domingues *et al*., 2017).


Figure 7: Coffee pulp pyrolyzed at 500C using Pyreg reactor

Figure 8: Coffee husk being burnt as disposal at Yayo, Illubabor, Ethiopia; Abera Melesse Ayalneh; http://www.northsouth.ethz.ch/programmes/sawiris/sawiris_4

When a dry process for removing coffee cherry skins is used, cherries are sun-dried and then dehulled. The waste biomass is referred to as coffee hulls or husks and is often piled in mounds. It is estimated that for every ton of green coffee produced 180 kg of husk are produced (Blinova *et al*., 2017). In some areas the husk mounds are burned to reduce their mass; however, the mounds often smolder rather than burn causing significant air pollution (Figure 8). It has been observed in some cases that the mounds self-ignite after rain events, creating a hazard to personal health and property.

The typical moisture content of coffee husks is low (~14%), making conversion into biochar much easier than with pulp. Yield from coffee husks varies from 43.5% - 31.6% when pyrolyzed at temperatures from 350°C to 550°C (Table 2). Fairly simple technologies exist to convert husks into biochar (see further information under Laos project). Larger scale continuous feed machines can also carbonize husks and generate a significant amount of energy that is used for drying beans or converted into electricity (see further information under Vietnam project).

Table 2: Biochar from coffee husks. Source: Domingues *et al*., 2017

Temperature	Yield	Fixed Carbon	Ash	Volatile Matter
[°C]	[% of feedstock]	[%]	[%]	[%]
350	43.5	52.5	12.9	34.6
+450	37.7	60.9	12.9	26.2
550	31.6	62.8	19.6	17.6

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Mucilage

Coffee mucilage is a sticky gelatinous material found underneath the pulp layer which constitutes up to 4% of the dry weight of the coffee cherry. Made up of sugars and pectin, the mucilage is often removed via fermentation. The resulting wastewater is very acidic and can be detrimental to waterways if released untreated. Given the high moisture content and low carbon content, mucilage is unlikely to be a viable biochar feedstock. However biochar could be added to compost made with mucilage to improve the composting process.

Parchment

Once the mucilage is removed and the beans are dried, the parchment layer is removed leaving what is known as "green coffee". Parchment is a hard shell-like layer that represents ~12% of the dry weight of the cherry. Due to low moisture content and relatively high lignin content, parchment is an ideal feedstock for biochar. It should be noted that Schweikle *et al.* (2018) found biochar made from 'coffee shells' (i.e., parchment) to be low in P and K content and less porous than biochar made from other feedstock (e.g. corn cobs, bamboo) with lower microbial activity when used as a soil amendment. As with most feedstocks the yields from carbonization decrease as temperature increases in this case decreasing from 33% to 24% as temperatures moved from 300ºC to 600ºC.

Chaff

Once green coffee beans have been shipped to consuming countries, residue management becomes the problem of the roaster or brewer. Coffee chaff (also called silverskin) is a lightweight material that comes off the coffee bean during the roasting process. For every 120 tons of roasted coffee, 1 ton of chaff is produced (Galanikas, 2017). Due to its insubstantial nature, chaff can be difficult to capture and burn directly although some efforts have been made to mix chaff with sawdust to create pressed fuel briquettes. Chaff has relatively high levels of minerals (potassium, calcium, magnesium, sulphur, phosphorus, amongst others) and can therefore be desirable as part of a compost or mulch blend. However, due to its matting tendency, hydrophobicity and a fairly low pH, it can present certain challenges when used in excess. Given the right type of handling and processing equipment, chaff may make a high-quality biochar particularly for applications needing high thermal conductivity and diffusivity (Quosai *et al.,* 2018).

Spent Coffee Grounds (SCG)

After coffee beans have been used to brew coffee beverages they take the form of spent coffee grounds (SCG). While there have been efforts to find valuable markets for SCG, the distributed nature of the end product makes it challenging to reach economies of scale to make this cost effective. Large retail outlets such as coffee shops often give away SCG to customers or at best send it to local composters. Efforts at converting SCG into biofuels and biochar have shown promise; for example, Vardon *et al., (2013*) compared the effect of using SCG biochar in soils against SCG on their own and a control (each of the three with and without fertilizer) and found that the SCG biochar showed the greatest enhancement in crop biomass yield. In another study, biochar made from SCG was successfully used to purify water and helped sorb chemicals such as mercury (Manariotis *et al., 2014*). Newer research has shown that SCG-derived biochars made using hydro thermal carbonization and doped with nitrogen can be utilized for CO_2

capture (Liu *et al*., 2018). These engineered biochars proved to be regenerable, losing only 6% stability after 10 adsorption/desorption cycles.

BIOCHAR PRODUCTION TECHNOLOGIES AND CO-PRODUCTS

Small scale cookstoves

Biochar-producing cookstoves have been used around the world for at least ten years. In cultures where the traditional three-stone fire cooking method is used, biochar-producing stoves can have the added benefit of significantly improved indoor air quality. Dry material such as coffee husks and coffee tree prunings make ideal feedstock for these stoves. In areas with limited forest cover, these stoves can reduce firewood collection, or purchasing needs if other feedstocks are used. The Kaffa Kocher project team in Ethiopia created a slightly larger stove that runs on dried coffee husks supplied by a local dehulling station and is specifically designed for local small business women that earn their living by cooking (http://www.kaffakocher.ch/).

Farm Scale Kilns

Biochar production technologies such as the Top Lit Updraft (TLUD) kiln, the more recently developed Kon-Tiki kiln (Figure 9) (*Schmidt and Taylor, 2014*) or simple retorts provide low-cost batch processing options to create larger amounts of biochar than those produced in stoves.

Figure 9: The Kon-Tiki kiln in Nepal; courtesy of Moira Schmidt

TLUDs are closed kilns often built using 200 liter metal barrels. TLUDs can produce approximately 25% yield per batch. While these units can be built inexpensively (<USD 100), certain low-cost models have short service life as the metal tends to buckle from the contained heat. The Kon-Tiki kiln is one of a growing number of different “flame-cap” kilns which produce biochar in an unenclosed cone receptacle. These kilns can generate more than 200 liters of biochar in 1 – 3 hours depending on the type, size and moisture content of feedstock, size of the kiln and technical operating skills. Flame cap kilns can process feedstock with higher moisture content and less pre-processing (e.g. size reduction) than TLUDs. Production costs in the developing world for the Kon-Tiki kiln can vary greatly; the most basic Kon-Tiki kilns are soil cone pit kilns. Metal flame cap kilns have been made in more than 70 countries with more sophisticated models starting at about USD 500. Both TLUDs and flame cap kilns require basic training to ensure good quality and safe biochar production and to ensure that particulate matter and GHG emissions are minimized. Cornelissen *et al*. (2016) compared

emissions from various types of flame cap kilns and more traditional kilns, finding that they reduced CO, products of incomplete combustion and NO_x.

A retort for biochar production is generally a closed metal container into which feedstock is put and then heated using other biomass. There are a variety of sizes which range from tin cans to large metal barrels (Figure 10). One advantage a retort may have over other low cost kilns is that it can carbonize a wide variety of feedstocks which may be more difficult to carbonize due to low air flow between biomass particles or high moisture content, such as coffee pulp or chaff.

Figure 10: Rotating retort for carbonizing coffee husks. Kaweri Coffee Plantation in Uganda.

Medium-Scale Pyrolysis

Medium-scale pyrolysis or gasification technologies customized to produce biochar are often referred to as Combined Heat and Biochar (CHAB) and are available in a range of sizes. Given the economic realities in most countries where coffee is cultivated, the high cost of large scale CHAB equipment currently available in the developed world does not make these systems economically viable even when the thermal energy co-product is factored into the equation. Medium scale equipment (<USD 50,000) applicable for milling stations is being tested or awaiting funding for use at a few coffee and biochar projects (Figure 11). In addition to mitigating the various waste disposal issues previously described, many of these reactors can provide energy which can be used for heating needs. Larger scale pyrolysis equipment (>USD 500,000) may be more appropriate for large coffee roasting operations in the developed world. These can reduce residue management costs while producing valuable by-products in the form of heat and electricity which can be used within the roasting operation.

Figure 11: Pyrolysis machine designed by Okozentrum, carbonizing coffee husks and generating energy in Vietnam.

Decarbonization Pathways Using Biochar

There are wide variations in coffee production techniques (polyculture vs. monoculture, shaded vs. unshaded, wet vs. dry processing, etc.) which lead to variation between studies of the carbon footprint of coffee. The operational carbon footprint will also vary as a result of the measurement approach, the parameters of the footprint and the specific production environment. Costa Rican shade grown polyculture coffee was found to emit 1.93 kg of CO_2e per kg of green coffee produced (Navichoc *et al., 2013*). Of these emissions, 53% came from cultivation, 33% from milling operations, and 14% were related to transport activities. The vast majority of the farm emissions, 95%, resulted from the use of chemical fertilizer. A broader carbon footprint study surveyed 116 coffee farms from five countries in Latin America encompassing all major types of coffee plantations (i.e. traditional polyculture, commercial polyculture, shaded monoculture, and unshaded monoculture) and found that emissions ranged from 6.2 – 7.3 kg CO_2e per kg of parchment coffee (i.e. parchment still intact) for polyculture and 9.0 – 10.8 CO_2e for monoculture production (van Rikxoort *et al., 2014*). This study showed the main sources of emissions included: soil emissions and production and application of fertilizers; decomposition of pruning and crop residues; fermentation and wastewater treatment.

Biochar can help to reduce coffee's carbon footprint in various aspects of cultivation and processing operations. Decarbonization using biochar can be achieved by both reducing current emissions as well as through long-term carbon sequestration. Through pyrolysis, the carbon existing in the biomass converts to a more stable form in biochar—this carbon would otherwise rapidly mineralize to CO_2 if either burned directly or left to decompose. Biochar production can sequester up to 50% of the initial carbon in biomass. This compares favorably to the low amounts retained after burning the biomass (3%) or after biological decomposition (<10 – 20% after 5 – 10 years) (Lehmann *et al., 2006*). The Mean Residence Time (MRT) of different biochars—i.e. the average amount of time that the carbon stays in the soil—has been found to fall mostly in the centennial to millennial time scales but varies considerably depending on the type of feedstock and production parameters (Lehmann *et al., 2015*).

Table 3 summarizes the various ways using biochar in coffee cultivation and processing can help to decarbonize as well as adapt to the anticipated impacts of climate change. Sequestration potential of carbonized coffee residues is not limited to below ground. Dahal *et al.* (2018) found that adding biochar made from coffee pulp, husks and discarded beans and added to existing coffee trees at a rate of 500 g per tree (equivalent to 5t/ha) not only increased soil carbon levels more than unamended soils after two years but also increased aboveground carbon stocks. On average, the carbon in coffee trees increased 46.8% in trees planted in biochar amended soils compared to 19.6% for unamended soils.

Adding biochar to soils used for coffee cultivation may also help to adapt to some of the impacts of climate change such as prolonged drought or increased disease pressures. Biochar may increase buffering of soil water management during periods of drought and, as discussed previously, it can improve the health of plants enabling enhanced disease resistance.

Table 3: Decarbonization pathways within coffee cultivation and processing

Stage in Supply Chain	Practice	Adaptation potential	Mitigation potential: *Carbon footprint reduction*	Mitigation potential: *Carbon sequestration*
Cultivation				
	Convert leaf litter, prunings into biochar		x	
	Add biochar as soil amendment	x	x	x
	Add biochar to pulp compost	x	x	x
	Reduce fertilizer inputs	x	x	
	Renewable energy (cook stoves)		x	
Post-harvest processing	Convert pulp to biochar		x	
	Renewable energy (CHAB)		x	
	Convert parchment to biochar		x	
	Create drying slabs from "*charcrete*"		x	x
	Waste water filtration of mucilage with biochar		x	

ECONOMICS OF BIOCHAR USE IN COFFEE PRODUCTION AND PROCESSING

The question of purchasing or producing biochar is one that must be answered on a case by case basis. Purchasing biochar may not be an option due to lack of local availability or cost. However, there is usually enough under-utilized biomass available on coffee plantations or processing mills which could be converted into biochar. Given the availability of low and sometimes no-cost biochar production equipment and relatively low labor costs, economics is not the main barrier for biochar production and use. It is more likely that education - on how to produce and why farmers should use biochar - is the largest barrier. However, for farmers or mill operators to be convinced to change their current operating procedures, they often need to understand the economic advantages.

The benefits of biochar from the research and demonstration projects on coffee plantations described in the following section focus on yield improvements, increased survival of coffee trees and reduced input costs. Yield improvements were attributed to improved water and fertilizer use efficiency as well as improved plant resistance to pests and pathogens. Cost reductions were largely focused on the need for less fertilizer but, in at least one case, could also be attributed to lower labor costs related to reduced need to replant coffee trees that die prematurely or are under-producing. The impact of less disease pressure from reduced land application of pulp has not yet been quantified.

At the milling station level, while there are multiple environmental benefits, translating these into reduced fines resulting from a failure to comply with regulations, or reduced disposal costs, may have more relevance in the developed world, where regulations tend to be stricter and more strongly enforced than in many developing countries. Using biochar to filter wastewater may be of keen interest as this may reduce the amount of water needed. The saturated char may become a new revenue stream for the mill. Use of renewable heat made from carbonizing residues to dry cherries can reduce reliance on fossil fuels and decrease costs.

New Revenue Streams

Although biochar produced on farms is ideally suited for use as a soil amendment, biochar produced at centralized mills could provide the raw material for a growing number of different products including livestock bedding, building materials, packaging materials, cosmetics, etc. Packaging material made using the biochar from coffee chaff, called 'chardboard', has been prototyped. This material has shown many beneficial attributes and cascading uses (Draper*, 2014*). Bricks and plaster have been made using charcoal in Europe and were found to be very effective at controlling humidity in warehouses and wine cellars. Additional testing showed that this material has added benefits related to insulation when applied throughout the building envelope. Plasters with charcoal incorporated into them could potentially be used in a number of different ways within the coffee supply chain. Pavements for drying coffee using this material instead of concrete would likely be cheaper as the materials could be made on site. It is also likely that the darker color would speed up the drying process.

COFFEE AND BIOCHAR DEMONSTRATION PROJECTS

In the first edition of this white paper, the authors identified more than a dozen projects which involved biochar as a component of coffee cultivation or processing activities. This edition highlights new projects started in Brazil, Colombia, Peru, China, Tanzania, Uganda, Ethiopia and Vietnam. Project coordinators for these projects identified various drivers for the coffee and biochar trials including:

- improved soil fertility through increased pH and water/nutrient management;
- improved soil resiliency to adapt to drought, heavy rain and pest;
- reduced dependence on fertilizers and other inputs;
- improved transplant survival rates for young coffee plants;
- ability to convert coffee residues into renewable energy and/or effective soil amendment; and
- improved composting functions when applied to coffee pulp compost.

Note that these projects encompass a range of implementation stages, testing protocols, and experiences; some have more details on crop effects, while others are focusing more on residue management and valorization. Along with these profiles, project managers identified additional projects planned in Burundi, Mexico, and elsewhere.

BRAZIL: FAZENDA DA LAGOA, NKG TROPICAL MANAGEMENT

Main Focus: Residue management & improved soil fertility

Fazenda da Lagoa grows Arabica coffee in high density rows. Soils in the area are highly weathered, acidic, with relatively low carbon content. Traditionally, lime has been used to moderate soil acidity.

Recently 52 ha of commercial new coffee trees were planted using a variety of different biochar treatments. Given the planting system used on the plantation, the biochar application process was modified from the one used in previous biochar trials managed by NKG Tropical Management. A 'V' shape trough of 80 cm depth is created, biochar compost was deposited (Figure 12), after which the furrow was closed, and the tree was planted. Twenty-five tons of compost was used per hectare with different amounts of biochar, from 2 to 6 tons per ha. In a small, comparative trial, 6 application rates between 1.9 – 22.8 tons biochar/ha were tested, which is currently under an ongoing evaluation process.

Figure 12: Biochar compost deposited in V shaped furrows prior to planting new coffee trees.

Given the promising results from earlier trials using biochar enriched compost for new trees, an additional trial using biochar compost to grow seedlings in nurseries was started in January 2018. Traditionally, seedlings have been grown in a mix of 70% soil and 30% decomposed chicken or cattle manure. This trial is experimenting with 10%, 20% and 30% biochar additions (v/v). Although only 6 months into the trial, the roots of the seedlings with the addition of biochar showed better growth than control. The seedlings are expected to be planted on the farm in late November 2018 at which point final evaluation will be done.

Hans Fässler, CEO of NKG Tropical Management, noted that there is keen interest though not sufficient knowledge about biochar production and use amongst coffee growers in Brazil. Ongoing work with coffee byproducts should demonstrate the merits of changing typical disposal strategies into a value-added process with resulting economic benefits. He believes that simple and cheap biochar production systems are key to enabling biochar to scale in coffee growing regions. Their next step in optimizing the use of biochar will be to look at filtering coffee wash water effluent with biochar as a means of harvesting the nutrients in the effluent. Results from experimental work will gradually define the optimal biochar and compost mixture for the farm's coffee-growing soils.

Peru: The Biochar for Sustainable Soils (B4SS) Project

Main Focus: improve coffee yield and quality, and share the knowledge generated on the use of biochar for sustainable land management

The Biochar for Sustainable Soils (B4SS) Project was funded by the Global Environment Facility and United Nations Environment from April 2015 to September 2018. The B4SS was implemented in China, Ethiopia, Kenya, Peru, Indonesia and Vietnam. In Peru, the B4SS was coordinated by Dr Brenton Ladd who has experience in undertaking biochar research work in Peru since 2011. The production of coffee is an important economic activity for some of the most economically disadvantaged people in Peru and the industry is facing challenges due to the roya rust fungus epidemic.

Figure 13: Coffee leaf from a plant grown with biochar (left) and coffee leaf from a plant grown without biochar (right) in San Ramon, Peru

Biochars were produced from green waste diverted from landfill in Lima. Various biochar formulations were designed to address the soil constraints identified by coffee growers in San Ramon, a small town in the central jungle of Peru, where the B4SS project took place. One of the leading farmers is growing coffee with one of the biochar formulations that the B4SS developed and found that the leaves of some coffee plants have been affected by the roya fungus, whereas there are no spots on the leaves of the plants that were planted in soils amended with biochar (Figure 13).

Although that experiment was not monitored by the B4SS project, Dr. Ladd suggests that biochar may have improved the mineral nutrition of the coffee plants and therefore enabled them to better construct the nitrogen-based defense compounds that may have allowed them to defend themselves against the insect vectors that spread the rust fungus. Participating farmers plan to continue the use of biochar in coffee cultivation. More research is required to explain the positive effects of biochar on coffee rust fungus observed in the B4SS project in Peru (www.biochar.international).

China: Yunnan Coffee Traders

Main Focus: coffee residue biochar for filtration

Yunnan Coffee Traders (YCT) in southwest China is focused on sustainable technologies for rural coffee growers and processors. Working with researchers at the University of Colorado Boulder, they have been carbonizing various coffee wastes (e.g. husks, parchment) to manage organic material as well as produce valuable products such as filtration media and fertilizers. YCT have also been testing low cost methods for pre-treating biomass to improve the performance of carbonized coffee waste for the removal of organic matter from coffee wastewater and drinking water sources, including any pesticide and pharmaceutical residues. Leveraging common techniques used to improve activated carbons (e.g. base activation), researchers have shown that coffee waste soaked in ash water, then dried and carbonized, improves the performance of coffee waste biochars in low-cost water treatment scenarios.
Researchers at the University of Colorado Boulder have also developed and piloted a low-cost method for regenerating saturated biochar using high heat in oxygen-limited environments. In some cases, the regenerated char is even more effective after regeneration, on a mass basis. Considering that the regeneration process consumes some biochar, the net result is a smaller mass of improved biochar that has a similar capacity to the larger mass of raw biochar. Discharging untreated wet mill run-off into waterways is an illegal practice in rural China, so YCT is tasking CU Boulder students with designing biofilters capable of removing organic materials from coffee washing effluent. When biochar production ramps up, they also plan to incorporate biochar in soils in test plots to evaluate the impacts of biochar on coffee yields and quality.

Colombia: LaPalma y El Tucan Coffee Farm

Main Focus: improve coffee quality and yield

The focus of this multi-year project which began in late 2016 is to assess biochar's impact on soil nutrients and quality, coffee yield and quality, and GHG emissions in an organically-managed coffee farm (Figure 14). Seedlings at two different stages of development, 2 weeks and 6 weeks, were planted in an area which had previously been poorly maintained and thus produced low quality beans. Biochar was created on-farm using prunings from shade trees and older non-productive arabica coffee trees which are normally either left to decompose or piled up and combusted. Carbonization was done using a metal Kon-Tiki kiln and the biochar was blended with compost (30% of blend was biochar, by volume).

As it takes coffee trees 3 – 4 years before they begin producing usable cherries, the results of this project are not complete. A number of measurements for soils and yields are being taken including:

- soil measurements: carbon, pH, available and total NPK, bulk density, cation exchange capacity and saturation;
- growth in the first 2 years: tree height, stem lengths, leaf count and possibly leaf analysis; and
- yield in more than 2 years: fruit produced per tree, weight and yield (volume) of cherries, weight and yield of sorted cherries, parchment coffee and green coffee.

Figure 14: Biochar compost being used to help retain moisture and boost growth of young coffee trees. Credit: R. Canal.

TANZANIA: BLACK EARTH PROJECT

Main Focus: Improve soil fertility and resilience

Based on biochar trial results showing 35% increases in yield with 50% reduction in input costs in Rwanda (described in the 1st version of this white paper), Radio Lifeline expanded coffee and biochar trials into Tanzania with funding provided by the German Investment Corporation (DEG) in collaboration with the Tembo Coffee Company and MIICO, a network of community agricultural development organizations. Farmers in Tanzania have been experiencing increased drought and are focused on improving water holding capacity in soils.

Low cost kilns made from used oil drums are used to make biochar from a variety of underutilized biomass including corn or coffee husks, tree prunings, etc. Field officers from Tembo and staff members from MIICO were trained on biochar production and use. This group then taught more than 7,000 farmers from both communities across Southern Tanzania how to make and apply biochar for growing coffee.

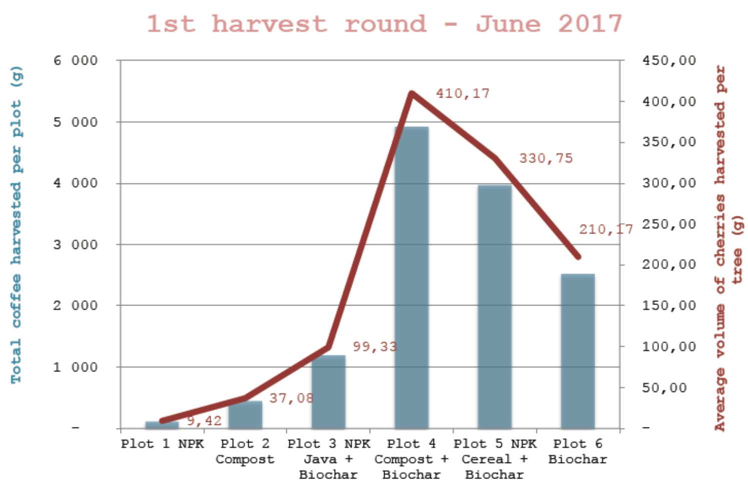

Figure 15: Tanzania Coffee trial results

Six different applications were tested on mature coffee trees: NPK only, compost only, biochar + NPK1, biochar + compost, biochar + NPK2, and biochar only. The first-round harvest showed a cherry production volume increase of 10 – 43 times more over fertilizer alone (Figure 15). It should be noted that this growing season included extended drought, hail and an outbreak of coffee cherry disease. The trees planted with biochar in combination with compost or fertilizer also produced more 'first grade' beans. In a tasting (also called cupping) analysis, coffee produced from beans harvested in the biochar enriched trees scored on average 2 points higher on the Specialty Coffee Association of America's 100-point quality cupping scale than coffee grown in soils without biochar.

Using a relative scale of -2 to 5, Figure 16 compares the general tree aspect (color, branches, leaves) and cherry volume (size and number) of the different applications showing a clear tendency for a combination of compost or fertilizer with biochar as providing more robust trees.

In a separate trial, freshly planted coffee seedlings with biochar + NPK or NPK alone in both full sun and shade scenarios were compared. In both scenarios, biochar-treated trees outperformed NPK-only treated trees after the first month.

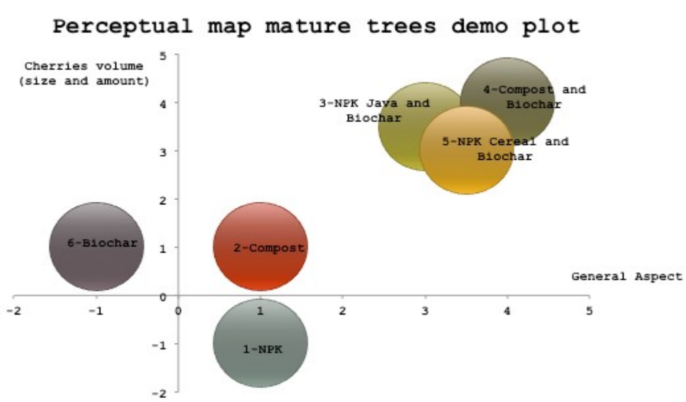

Figure 16: Comparison of biochar trial results in Tanzania; source: Peter Kettler

LAOS: JHAI COFFEE HOUSE

Main Focus: Residue management & improved farmer livelihood, natural farming

Filanthrope is a non-profit organization which works with and supports indigenous, ethnic-minority coffee growing communities in India, Indonesia, Laos and Vietnam. The focus of their work is to empower communities with knowledge and technical skills about that which they rely upon for their livelihood: coffee. Filanthrope works to realign the coffee value-chain in order to alleviate poverty, re-establish healthy ecosystems, and create a healthy social environment for communities based on principles of compassion, truth, dignity, and open-source knowledge sharing.

Working with the Jhai Coffee House in Laos, Filanthrope purchased a gasifier powered roaster (USD 250) capable of roasting 2 kg of coffee per batch (Figure 17). The unit uses less than one watt-hour of electricity per kg of beans and runs on coffee husks. The gasifier enabled the community to sell brewed coffee for USD 40/kg compared to previously earning only USD 3/kg for green coffee, thereby paying for itself in a few hours.

The resulting biochar can be used in compost or to harvest and filter the sugars and nutrients from coffee waste water after which it is converted into animal feed additive.

Figure 17: gasifier used to roast coffee beans. Credit Paul Olivier, inventor of the micro-gasifier.

UGANDA: NKG TROPICAL FARM MANAGEMENT (NEUMANN KAFFEE GRUPPE)

Main Focus: Residue management & improved soil fertility

NKG Tropical Farm Management grows Robusta coffee on 1,600 ha on the Kaweri Coffee Plantation in Uganda. Large amounts of coffee residues are generated from the milling process. Biochar has been produced on the farm using a simple drum over a fire since 2016. Initially, biochar was made from wood pruned from coffee trees, but nowadays it is made exclusively from coffee husks as both a residue management process and as a means to improve soil structure to ultimately improve water and nutrient management.

A single laborer can produce 64 tons of biochar per growing season which is incorporated into compost made up of 20% coffee husks, 50% pulp, 20% biochar and 10% top soil. The composting process is still being optimized but currently takes about 8 weeks to finish. 50L/plant of biochar-compost blend is used for new field plantings per tree, of which 2.3 kg is biochar. The blend is deposited in a hole (80 – 100 cm in diameter and ca. 30-40 cm deep) prior to placing the tree. On average the farm spends USD 1,050 per ha for the biochar compost.

In 2016, the first 4.5 ha of new trees were planted and a control set of 100 trees was planted nearby so that a comparison could be made. While it seemed that the biochar-enriched compost initially immobilized nitrogen 2 months after planting the trees were growing well and there is now a visible size difference in these trees. An additional 18 ha of new trees were planted with biochar compost in 2017. The farm aims to plant about 20 ha per annum onwards, using biochar compost, although mixture and application rates may change, based on field results.

NKG Tropical Farm Management, a Neumann Group owned company, manages coffee farms in Latin American and Africa. Their focus is on producing better, more sustainable coffee. They have been working towards rolling out biochar use in a growing number of the farms under their management in Uganda, Brazil, Mexico and other countries.

Ethiopia: The Biochar for Sustainable Soils (B4SS) Project

Main Focus: Residue management & improved soil fertility

The Biochar for Sustainable Soils (B4SS) Project in Ethiopia was carried out by Jimma University from April 2015 to September 2018. The B4SS project helped to expand the long-term trials that Jimma University has conducted since 2011 on fields managed by both researchers and farmers to evaluate the effects of various biochar formulations on maize and soybeans. Around Jimma, coffee residues are a health hazard since this material is left to decompose in uncontrolled piles that attract flies and other insects. B4SS has leveraged this waste to produce biochar. The materials of the biochar formulations prepared by Jimma University include compost from coffee husk, coffee husk-derived biochar, cattle and chicken manure, chemical fertilizers, bone meal, and bone char. On average, the formulation that consists of biochar from coffee husk co-composted with animal manure in concrete blocks for about three months (Figure 18) has resulted in savings of about 40% NPK fertilizer compared with the

Figure 18: Biochar made from coffee husk is co-composted with animal manure in concrete blocks for about three months in Jimma University, Ethiopia

application of 100% NPK fertilizer. These trials are used for demonstration purposes and have helped to share knowledge and practice of using biochar for sustainable land management (www.biochar.international).

VIETNAM: MINIMIZATION OF INDUSTRIAL WASTE FOR LOW CARBON PRODUCTION

Main Focus: Gasifying coffee waste to provide heat for coffee bean drying

Drying coffee beans in Vietnam has become more challenging due to more erratic weather patterns. A project funded by the State Secretariat for Economic Affairs (SECO) demonstrated that pyrolysis of coffee husks can provide sufficient heat for drying beans and also produces biochar. The project also sought to reduce or reuse organic residues from coffee in order to improve the local environment and reduce GHGs.

The PPV300 unit was developed by the Swiss company Ökozentrum (Figure 19) and delivered to a 30-member coffee co-op in Vietnam where it converts moist coffee pulp into K-enriched biochar (total 33 kg/h) while also supplying 150 kilowatt of heat for the dryer with a capacity of four tons of green coffee. The pyrolysis equipment utilizes medium moisture content feedstock (up to 54% has been tested, but the recommendation for customers is a maximum of 40%) and the exhaust gas complies with the most stringent regulations. The resulting biochar produced from coffee husks qualifies under the European Biochar Certificate regulations.

Figure 19: PPV300 unit in Vietnam. Photo source: https://www.youtube.com/watch?v=3rWDJ4qwVhM

Ökozentrum has calculated that for every kWh of energy created, 900 g of CO_2-e removed by plants enters the pyrolysis system. The process emits 400 g CO_2, which results in a net removal rate of 500 g CO_2 per kWh of useful energy, or -75 tons CO_2 for a unit of this size during one harvest season running 10 weeks x 100 hours (4 days per week for 24h each day). Using this technology could substantially reduce the carbon footprint of coffee production. After the coffee harvest season, the pyrolizer could run with rice husk, cashew shells and bamboo - all substrates which have already been tested.

Ökozentrum estimates that from an economic perspective fuel savings contribute about a third of the overall benefit while the biochar output could contribute an even larger economic benefit when local markets for biochar are available or created.

Figure 20: Photos from Pyrolysis Technology Improves Coffee Quality workshop. Source: Ökozentrum

In 2017 a workshop entitled 'Pyrolysis Technology Improves Coffee Quality" (Figure 20) was hosted by the United Nations Industrial Development Organization (UNIDO), REPIC, Hanns R. Neumann Foundation (HRNS), Viet Hien Company Ltd., Viet Nam Cleaner Production Center (VNCPC) and SOFIES, a Swiss consulting company with the aim of disseminating information on the benefits of pyrolysis for low cost, renewable heat and biochar production.

DISCUSSION AND FUTURE RESEARCH

An increasing number of biochar and coffee projects are underway around the globe since the publication of the 1st Edition White Paper. Organizations such as Radio Lifeline, NKG Tropical Farm Management, and Ökozentrum have secured funding and support to conduct new biochar trials or biochar production scenarios. Dr. Ben Evar, after initiating trials in Colombia, drafted a biochar and coffee trial methodology, currently unpublished but has been shared informally with other projects to aide in establishing and reporting on biochar trials on coffee farms. In addition, characterization of biochar made from various coffee waste streams has progressed, though there will always be more that can be learned by using different technologies and different production parameters.

Yet there remains much work to be done to scale these efforts up so that they can benefit a greater portion of the millions of hectares used to grow coffee and the farmers that tend them. Below are a few recommended areas of focus that could inform and support adoption of biochar production and use within the coffee supply chain where excess coffee residues are problematic or soils have constraints that biochar application could address.

Education on the Benefits of Biochar & Biochar Production

Peter Kettler, Founder of Radio Lifeline, has perhaps done the most to further education amongst coffee farmers in terms of soils, soil amendments and how biochar can improve soils while reducing off-farm inputs. Creating a 'train-the-trainer' educational program enabled thousands of small farmers in Rwanda and Tanzania to learn not only how to make and use biochar, but also what it does to the soil and why they should use it to improve soil fertility and resilience.

These types of programs need to be duplicated and customized for different cultures, different growing scenarios (e.g. sun vs shade, mono versus mixed, etc.) and deployed. Partnering with local community agricultural organizations or coffee co-ops would seem like a wise strategy.

In addition to educating growers, other major players within the supply chain could benefit from more education on the benefits of biochar including buyers, brewers, certification companies and development agencies. There are many opportunities to advance knowledge on biochar amongst the coffee community including trade shows, expos, conferences, cupping events, etc. For example, Kettler spoke about his success in Tanzania and Rwanda at a recent World of Coffee event which generated interest from attendees.

Cost Benefit Analysis Templates

While a cost-benefit analysis at the farm or milling station level would be useful, such an analysis would be highly specific to the individual parameters of a particular farm or processing operation. Nevertheless, the development of a standardized approach to quantifying the costs and benefits of using biochar within the coffee industry could help to develop an evidence base on net benefits and drive adoption of biochar as growers and millers could more quickly determine payback timeframes and understand potential biochar uses and new revenue opportunities.

NKG Tropical Farm Management has begun to quantify the costs per hectare of applying biochar-enriched compost to new plantings in large coffee plantations. Moving forward, it will be possible to compare the benefits to these trees in terms of yield, disease resistance and tree survivability with those from a set of untreated trees. This type of information would be beneficial for smallholder farmers as well, to understand the reduction of off-farm purchases such as fertilizers and to understand the impact, if any, on tree health and survival from using biochar-enriched composts.

On-going coordination amongst coffee and biochar projects

As occurred while researching the first edition of this white paper, several new coffee and biochar projects were identified, and few are in communication with other project teams. These newer projects were carried out by practitioners with varying levels of knowledge on the topic of coffee cultivation using biochar. Project teams were eager to learn about best practices, lessons learned, application methods, equipment, and several other aspects of project design. While the Ithaka Institute and IBI were able to share initial information amongst the teams, and to connect them with each other during the writing of this second edition white paper, an on-going coordination effort would likely prove very beneficial in assisting the various coffee and biochar project teams to share information and lessons learned. It may also facilitate a wider adoption of the use of biochar in coffee production systems throughout the coffee growing community.

Demonstrations of biochar & Biochar Production within the Coffee industry

The coffee and biochar projects presented in this white paper are all demonstrating promising results spurring many of the project teams to replicate and expand their biochar trials. However, few are taking full advantage of all the benefits from biochar production by using all by-products (e.g. heat, biochar, potentially electricity, wood vinegar, etc.). Some project developers are focused on residue management, others on renewable energy production or water filtration and others on improved soil fertility. All of these are important but do not represent a holistic perspective which can bring maximum benefit and economic development to growers and processors. Designing a demonstration project that takes full advantage of all potential benefits and quantifying the socio-economic and environmental benefits could be a persuasive tool for obtaining funding for such projects.

Optimizing Biochar in Coffee Compost

While biochar and compost is a topic that has received much attention and research, the compostable residues available from coffee cultivation and processing have not undergone as much research when combined with biochar. As these residues have certain elements that may be less beneficial to soils (i.e. caffeine, tannins), fine tuning the compost process to minimize these elements is important. Adding biochar to this compost at different rates, for different periods of time and in combination with other organic materials (e.g. animal manure) should continue to be researched. Trials using different types of biochar-enriched compost should be documented to understand which ones work best in different scenarios (e.g. nurseries, new plantings, mature trees, sun vs shade grown, etc.).

QUANTIFICATION OF CARBON REDUCTIONS USING BIOCHAR

Although this report has provided a high-level overview of the potential avenues by which the introduction of biochar production and use into the coffee supply chain could reduce the carbon footprint of coffee, much more research is required to quantify the specific GHG emission reductions under different scenarios; e.g. reduced emissions from carbonizing versus composting and land application of coffee residues, renewable energy produced from carbonizing residues versus using fossil fuels for drying cherries, etc. Once these are quantified, it may be possible that financing for biochar production equipment could come from the sale of carbon credits.

The abundance and underutilization of coffee residues represents a potential source of carbon sequestration when used as biochar for soil amendment or embedded in other long-lasting products. Extrapolating available information on 2017, coffee production, reported as 60 kg bags of green coffee, and the relative weight of coffee residues relative to green beans generates nearly 2 times the weight of the green beans. Using biochar yield data for the different residues that more than 7.5 Mt of biochar could result (Table 4). Applying the relevant fixed carbon amount for each waste stream shows that the potential CO_2-e just from a soil carbon addition perspective would exceed 12,000,000 Mt. Factoring in reduced emissions from avoided fossil fuel energy, fertilizers and other sources would likely raise this number much higher. At a time when cutting GHG emissions is critical, carbonizing residues which are often burned or discarded could be a viable method for companies to reduce their carbon footprint.

Table 4: Potential carbon sequestration from coffee residues

2017 Green Coffee Production (159.55M bags, 9.6 MMT)

Residue	as % Green bean weight	Global volume (MMT)	Biochar yield (%)	Biochar yield (MMT)	Fixed Carbon	Total Carbon (MMT)	CO2e (MMT)
Pulp	1	9.60	52±1	4.99	29.60	1.48	5.42
Parchment	0.25	2.40	27±6	0.65	18.10	0.12	0.43
Silver skin/chaff	0.16	1.54	34±2	0.52	20.60	0.11	0.39
Spent coffee	0.542	5.20	36±4	1.87	18.40	0.34	1.26
TOTAL						**2.05**	**7.51**

Pulp, parchment, silverskin percentages derived from International Coffee Organization reporting standards; Source for data on biochar yield and fixed carbon: Olani, 2018.

CONCLUSION

Although the use of biochar in coffee cultivation has continued to expand over the past three years, this practice is still in its infancy. While it is encouraging that new players within the coffee industry are recognizing the value of biochar production and use, there remains a significant part of the sector that has never heard of biochar, or that are skeptical of the potential benefits offered by its production and use. Investing in biochar education throughout the supply chain would help increase the interest and use of biochar. It would also be helpful to have more peer-reviewed literature on agronomic and climate change effects of biochar, to provide more quantitative evidence on biochar's impacts. This type of academic rigor could help convince the coffee industry to incorporate biochar production and use throughout the coffee supply chain. It might also help underpin policy support to decarbonize the industry.

This White Paper should serve as a first step in clearly articulating the potential benefits of biochar in enhancing yield and profitability of coffee production, including for smallholders, and enhancing sustainability of coffee supply chains. Furthermore, it demonstrates how biochar can reduce climate impacts while also improving resilience to climate change of the coffee industry.

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